THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

TASK S-22

U.S. DEPARTMENT OF COMMERCE

MARITIME ADMINISTRATION

in cooperation with

BATH IRON WORKS CORPORATION

FINAL REPORT

WELD DEFECT TOLERANCE STUDY

Prepared by:

Sun Shipbuilding & Drydock Co.
Dr. L. W. Sandor

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1980**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The National Shipbuilding Research Program Task S-22 Weld Defect Tolerance Study**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Building 192 Room 128 9500 MacArthur Bldg Bethesda, MD 20817-5700**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**126**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

EXECUTIVE SUMMARY

The principal objective of this project was to examine the possibility of decreasing the high cost **of** weld repair in commercial shipbuilding. The approach involved a comprehensive survey of the international literature, as well as existing codes, consultation of world famous experts and quality control data acquisition from four major U.S. shipbuilds. The fracture mechanics analysis case history of the Alaskan oil pipeline was also reviewed. It was recognized that while a pipeline is not completely analogous to a large surface vessel, the merits of the relevant fracture mechanics principle were, however, convincingly established in a giant industrial project for the first time.

The fitness-for-purpose philosophy represents an important advancement over present weld acceptance standards, which in general are much too conservative and workmanship-based. The predominant failure mode in commercial ships is reported to be fatigue, caused mostly by poor design details and joint misalignment. The occurrence of brittle fracture is rare. Its consequence is, however, much more serious than that of fatigue. The critical size discontinuity for fatigue is considerably larger than for the brittle fracture mode.

Weld discontinuities as sole causes of in-service ship failures rank low among the numerous causes reported. The five major categories of discontinuities include:

1. Crack or crack-like
2. Geometric
3. Lack of fusion and lack of penetration
4. Slag
5. Porosity

Of these five discontinuities, the literature regards porosity and slag as the least harmful type. Weld repair is not synonymous with improvement. The attendant undesirable consequences of weld repair may be the increased residual stress, the degradation of microstructure, the lowering of fracture toughness, the introduction of new discontinuities and the aggravation of previously undetected discontinuity.

In contrast to the above, a statistical analysis of the data received from American shipyards showed that slag inclusions and porosity constituted the bulk of the weld repair activity. The repair and rework costs were estimated to have ranged from $0.6 million to well in excess of $1.0 million per ship.

The “Quality Bands" format of new weld acceptance standards for slag and porosity seems to be quite popular in the world literature, and it is estimated that such an approach has the potential of saving 50-100% of the weld repair cost experienced now. It should also be noted that as nondestructive testing, evaluation and inspection techniques continue to improve, the tendency may be to require even more unnecessary and costly (dollars <u>and</u> productivity) rework.

It is hoped that the rationale contained in this report will provide the basis for near-term initiatives to reduce unnecessary ship weld repair costs. The extent to which existing standards for slag and porosity might be relaxed along the lines of “Quality Bands” should be determined by a special Task Force, a body composed of experts representing classification societies, shipyards, owner/ operators, design offices, academia, U.S. Coast Guard and Navy.

In response to industry recommendations resulting from a preliminary review of this report, an additional effort was under- taken to assess the significance of weld discontinuities in naval surface ships constructed from mild steel. The results of that investigation will be published as a separate document as Part II to this “Weld Defect Tolerance Study” report.

Sun Shipbuilding would like to thank Mr. John Mason, MarAd Program Manager, Bath Iron Works, and the members of SNAME Panel SP-6, Standards and Specifications, for awarding this subcontract and providing guidance as well as valuable information. Appreciation is also extended to the U.S. Maritime Administration for sponsoring Task S-22 under the Shipbuilding Standards Program.

CONTENTS

APPENDICES

I. INTRODUCTION

The intent of the present program was to conduct a state of the art review in the field of weld defect tolerance for commercial shipbuilding applications. Specifically, this study was directed at examining the possibilities of decreasing the high cost of weld repair and outlining future trends and options for new weld discontinuity standards founded upon more rational engineering principles than the present codes. All along, it has been recognized that such new standards would take a considerable period of time to both develop and gain industry acceptance. To this end, a project of this type should serve to act as a catalyst or a means of initiating and ultimately obtaining the consensus of the shipbuilding industry using the American Society for Testing & Materials as a forum. It is hoped that the findings of this program will set in motion the elements necessary to bring about these stated objectives.

Corporate Science and Technology of Sun Ship was awarded in August, 1978, a subcontract on "Weld Defect Tolerance Study" by Bath Iron Works as part of the Shipbuilding Standards Program.

The weld defect tolerance study presupposes that introduction of discontinuities into welds is unavoidable, regardless of type of process used or degree of care exercised. <u>Fortunately, not all defects are harmful</u>. Thus, not all defects require repair. In fact, repairing an innocuous discontinuity would entail an unnecessary cost added to the manufacture of a weldment (in our case, a ship).

The real meaning and purpose of weld defect tolerance study is not the lowering of product quality, but rather the outlining of the conditions for avoiding unnecessary weld repair costs and weldment degradation in general. It is a philosophy based upon a “fitness-for-purpose” criterion.

The impetus for this program were advances in the field of fracture mechanics. Fracture mechanics is a relatively new engineering discipline which is basically an analytical technique to assess the effects of discontinuities on the mechanical behavior of structural components. With this analytical tool, the effect of weld discontinuities could be determined with a much higher degree of certainty then earlier empirical “rule of thumb” type approaches. Recently, with the use of fracture mechanics, new defect acceptance codes have been proposed. In addition, fracture mechanics has made it possible to analyze the effect of defects in certain welded structures such as the Alaska pipeline (See Section II.I).

Initially, it was thought that there could be significant benefit in using the fracture mechanics analytical approach on a case by case basis to assess the effect of defects on shipbuilding hull welds. This type of approach is similar to the post welding analyses performed on the Alyeska pipeline. However, this study will show that this case by case analysis does not appear to have promise as a potential cost savings tool for commercial shipbuilding. The significance of weld discontinuity takes on different design and inspection meanings depending on failure modes observed historically in a given welded structure. In this context the three principal failure modes are brittle fracture, fatigue, and elastic-plastic (or mixed mode). It has been estimated that 70-90% of all industrial failures including ships involved fatigue (l-3). The design philosophy for the prevention of fatigue failure lies in careful details design (4). Whilst the objective should be to avoid failure by any of these modes, the consequences of fatigue failure are less disastrous than those of brittle or elastic-plastic fracture. For fatigue failure modes, larger size discontinuities can be tolerated and catastrophic failure modes would largely be eliminated, particularly when the ship is operated above the ductile-to-brittle transition temperature. Fatigue failure mode gives warning time. For brittle fracture conditions, the design philosophy is the most rigorous, since the critical discontinuity size is very much smaller than for general yield cases. The normal philosophy with brittle fracture is to ensure that this mode of failure cannot occur by selecting materials which are ductile under the design operating conditions. For brittle materials the critical discontinuity size is very much smaller than for materials that would fail by general yield. Naturally, the design philosophy required if brittle materials are used is considerably less appealing from a Practical as well as a cost standpoint. The use of such materials in welded structures such as ship's hulls is particularly to be avoided because such structures are inevitably stressed into the yield range as a result of locked in stresses (residual stress) due to weld shrinkage and because of structural discontinuities.

Creep-Rupture failure mode is not relevant to ship failures because it occurs at elevated temperatures.

The fracture mechanics approach to fatigue assessment makes the tacit assumption that discontinuities are present in welds. Crack initiation is therefore inconsequential, but crack propagation is the overriding consideration.

One of the difficulties that was encountered in this study was that ordinary strength structural steels are used for commercial ship hulls. In terms of chemical composition these steels are referred to as carbon-manganese steels. These steels are obtainable in different grades as a result of different steel making processes and/or chemistry. The net result of these differences is a rather broad scatter in the fracture toughness or fracture resistance of these steels. This makes it somewhat difficult to make definitive statements at the present time regarding the acceptability of specific defects without specific fracture information on a given weldment.

The approach taken for studying the real meaning of fracture mechanics principles in assessing the bona fide role of discontinuities in commercial ship hull welds was the following:

A critical survey of the available world literature with a specific view toward usefulness in shipbuilding was conducted. World renowned experts from universities, research institutions, and industry relative to the scope of this study were consulted. All aspects of pertinent fracture mechanics principles based on known failure modes that have occurred in commercial ship hulls **were** reviewed. Nondestructive test methodologies, shipbuilding codes, current understanding of weld repair, and shipbuilding quality control data as exist today were examined. The most pre-eminent case history of fracture mechanics principles applied to the world's largest, single pipeline project was analyzed. A synthesis of all this information was made and translated into a benefit to the U. S. commercial shipbuilding industry.

Finally, formats for new weld acceptance standards are proposed and directions for improving the overall shipbuilding quality with a minimum of expenses involved are suggested.

II. DISCUSSION

II.A. World Literature Survey

The significance of weld discontintities is assessed on the basis of their effect on the life and integrity of a welded structure. The spectrum of weld discontinuity influence can range from harmful to innocuous. Consequently, weld discontintities are ranked in accord-cc with the nature of their influence upon the behavior of the structure which is a function of:

1. Geometric shape of the discontinuity,
2. Acuity of the extremities of the discontinuity,
3. Location of the discontinuity in the weld as well as ship location of the weld,
4. Amount and distribution of the discontinuity in the weld,
5. Species of the operating stresses and their magnitude,
6. Environmental conditions (corrosion, temperature),
7. Welding processes,
8. Design conditions and presence of structural discontinuities,
9. Material thickness,
10. Rate of loading,
11. Size of weldment,
12. Transients during ship operations,
13. Microstructure in general,
14. Material chemistry.

Defect-related factors affecting the significance of weld discontinuities are type, size, shape, quantity, distribution, orientation and location. To determine the significance of a discontinuity in a weld by means of fracture mechanics principles requires quantification of principal stresses, environmental parameters (corrosivity, temperature), design conditions (stress concentration), manufacturing conditions (joint misalignment), defect dimensioning (depth, length) and fracture toughness determination.

In decreasing order of harmfulness, the literature has recognized the following weld discontinuities:

1. Crack or crack-like discontinuity,
2. Geometric discontinuity,
3. Lack of fusion (LOF) and lack of penetration (LOP),
4. Slag inclusion,
5. Porosity

There are two other ways of categorizing weld defects, namely:

1.1 Planar

1.2 Nonplanar

and

2.1 Surface

2.2 Buried

2.3 Through thickness

Let us now turn to the discussion of the five principal categories of weld discontinuities.

1. Cracks or Crack-like Discontinuities

Cracks are regarded as the most detrimental defects owing to their sharp extremities. The acuity of the extremities of cracks or crack-like discontinuities gives rise to very short fatigue crack initiation time; hence, crack propagation is important.

Surface cracks are most harmful and are also subject to environmental effects, which amplifies the adverse influence of cracks, particularly in low toughness materials. Although not without a total unabiguity, most experts in the field of fracture mechanics agree that cracks ought not to be tolerated in products especially in their manufacture. If, on the other hand, a crack is detected in service of the welded product, one can resort to the utilization of relevant fracture mechanics principles by which to determine the life expectancy using the lower bound level as Harrison suggests (5). Conservatism lies in his approach, when suggesting lower bound conditions.

2. Geometric Discontinuities

These discontinuities are in general associated with the weld profile, although misalignment, weld spatter, arc-strikes and burn-through also fall in this category. In spite of their pronounced harmful influence on fatigue strength, welds are produced with undesirable contours. Large reinforcement angles and discontinuities at toes of fillet welds are particularly deleterious. Gurney (6) reported that the critical size of a geometric discontinuity in fillet welds for a given leg length decreased as the plate thickness increased.

If the crack propagation rate is slower in a given metal than in another, the critical size of the weld discontinuity can be increased. Geometric discontinuities are influential in static behavior of welded structures to the extent that they give rise to stress concentrations and change the load bearing cross-sectional area.

3. Lack of Fusion and Lack of Penetration

Lack of fusion is when the weld metal has not fused (melted) into the side wall of the joint. When the weld metal has not penetrated to the bottom of the weld joint, it is called lack of penetration.

The treatment of LOF and LOP must be related to the ductile-to-brittle transition temperature of the specific ship steel in question since they behave differently when the steel is above or when it is below the transition temperature (TT). Below the TT, both LOF and LOP are potentially harmful. They trigger brittle fracture. If the steel is above the TT, they are slightly worse than slag inclusions or porosity. This, then, suggests the importance of defining the exact TT and the service conditions of the ship.

The effect of LOF and LOP can be masked by weld metal over-matching and reinforcement. The direction of the applied alternating stress with respect to LOF and LOP is very important. When the applied load is parallel to LOF and LOP the effect is minimal, and the harmful influence is maximum when the direction of stresses acting on these discontinuities is perpendicular.

This alludes to possibilities in different QC requirements for shell butt welds from shell seam welds.

In high strength steels initiation time is minimal according to Professor Lawrence, et al. (7). This apparent difference explains the greater sensitivity of high strength steels to weld discontinuities. If the ship steel is in the upper shelf region, or above the crack-arrest-temperature (CAT), an initiated crack is normally arrested once it leaves the tensile residual stress field and the degraded microstructure region.

The significance of LOF and LOP in an aluminum alloy of Al-4.4% Mg welded by MIG was investigated by Screm and Frattini (8). They found that LOF and LOP were much more serious defects than undercut, surface irregularity, macro- and microporosity. The fatigue strength of this aluminum alloy in a 12 mm test specimen thickness was reduced 60% by the presence of LOF and/or LOP.

LOF/LOP have blunted extremities, therefore, they have been compared to slag inclusions by many researchers. How much LOF/LOP may be allowed depends upon their “aspect ratio”, location, and orientation with respect to the applied load. The literature regards LOF/LOP more deleterious than inclusions and certainly more than porosity.

4. <u>Slag Inclusion</u>

While there are several welding methods used in shipbuilding today, still the most widely utilized ones are first the shielded metal-arc and then the submerged-arc processes. Both methods are potential sources of slag inclusions that may be entrapped in the weld. Multiple pass welds are more prone for non-metallic inclusions than single pass welded joints.

Fluxes exert a pronounced influence upon the properties and soundness of the resultant weld (9). Basic fluxes promote low oxygen and/or sulphur contents in the weld metal, thereby minimizing the formation of non-metallic inclusions. In a broader sense, the type of submerged-arc flux used will influence the quantity and species of foreign particles present in the weld bead. Of the several manifestations of the influence of flux, the discussion herein is confined to slag inclusions. These non-metallic inclusions represent an incoherent phase in the surrounding matrix. In the context of fracture mechanics, these foreign particles are less harmful than cracks or crack-like discontinuities due to configurational differences. The tensile strength of the material is reduced in proportion to the projected area of the slag. This effect is smaller on the yield strength. The tensile ductility is reduced significantly by the presence of slags (1). Stress concentration induced by a foreign particle is less by virtue of not creating a void in the structure than that caused by porosity irrespective of material containing these defects (1, 10). The significance of slag inclusions is treated in terms of their size, amount, distribution and location within the weldment.

Fatigue test results are listed in order of increasing length of non-metallic inclusions and plotted on a log S versus log N diagram; where, S denotes the stress range and N signifies the number of cycles (endurance). The diagram usually contains five arbitrary Quality Bands: I, II, III, IV and V. (See Appendix III).

Furthermore, the “Quality Bands” are set up for 97.5% or 99.5% confidence levels (11), also called probability of survival (12).

Each band corresponds to a specific fatigue strength required in a given structure in conformance with design criteria. For a given size (length) slag particle as the stress range increases, the number of cycles decreases. On the other hand, the shorter the length of a non-metallic inclusion, the higher the endurance limit for a specific stress range imposed on that weldment.

The quality categories have been set up on the basis of (a) “as-welded” and (b) “stress-relieved” structures (12). Various proposals can be found in the international literature with regard to the treatment of defect interaction criteria and multiple slag inclusions. For example, the British Draft Standards (12) takes the view that “where multiple slag inclusions occur on the same cross section and the distance between the defects is less than 1.25 times the height of the larger defect, they should be treated as a single planar defect with an overall height equal to the distance between the outer extremities”. If the detected non-planar defect is smaller than that given in tables set up for (a) as-welded and (b) stress-relieved structures for the respective quality categories and survival probabilities, the defect is acceptable (12).

In terms of influence on fatigue, slag inclusions are similar to porosity, which will be discussed next. Thus, analogous criteria can be applied to slag (13). The international literature agrees on extending a considerably greater tolerance for slag inclusions and porosity than existing codes permit (9-11, 14-15). This literature survey indicates that “Quality Bands” as an approach to discontinuity acceptance standards have a broad support throughout the world. The specific levels of these bands may, however, be subject to certain engineering critique.

5. <u>Porosity</u>

Porosity is regarded by a preponderance of the investigators as the least harmful of all discontinuities. The influence of porosity, however, is treated according to its location; i.e., surface or internal pores. In earlier publications, the shape of porosity was believed to matter. Between spherical porosity and herringbone porosity the former was regarded as the least harmful of the two. Harrison (16) claims that herringbone porosity is no more harmful than spherical porosity. He further asserts that both types of porosity which occur in “normal amounts in practice is acceptable for quality levels below “V”. Boulton (10) mentions that surface porosity has a detrimental effect on fatigue strength, particularly when the weld reinforcement is removed. To improve fatigue life of weldments containing surface porosity, the weld toe should be dressed to minimize stress concentration. It has been observed that a fatigue failure instead of originating at buried slag inclusions does so at surface porosity. Pores in the surface are relatively more detrimental than internal pores of the same size and amount over a given weld length. Fatigue strength is most susceptible to the presence of stress risers, therefore, superficial porosity gives rise to a reduction in fatigue strength. The influence of porosity can be minimized by weld reinforcement and overmatching. When the strength of the weld metal is considerably higher than that of the substrate, it is referred to as overmatching. One has to distinguish between porosity in butt welds and porosity in fillet welds. The reason being, butt welds are relatively more critical in terms of application than fillet welds. The surface tension and viscosity of both the liquid weld metal and the molten flux are important in controlling the propensity of the pore to rise to and escape from the surface.

In scattered form, porosity in amounts of up to 5-7% is considered by the international literature as having no influence on yield strength, ultimate strength, reduction in cross-sectional area and slow bend ductility. Therefore, when static properties are the controlling parameters in weldment behavior, code restrictions can be relaxed by a factor of 2-4 even for critical applications (l).

With preference to high cycle fatigue, the porosity is the least harmful so long as the reinforcement of the weld is not removed (17-19). When the reinforcement is removed, porosity may be a nucleation site for fatigue crack extension at low levels of porosity (17-18). Initially, the rate of decrease in fatigue strength is appreciable (up to 50%), but after reaching about 5% in porosity the fatigue strength reduction rate decreases (17-19).

To influence the fatigue strength of fillet welds, porosity is to be Located in the root and be present in large amounts. Harrison (20) did a comprehensive analysis of all the available information in the literature about the relationship between porosity and fatigue stress of steel butt welds. He plotted the data on a log S - log N graph and established five quality categories for 0, 3, 8, 20 and 20 + % porosity levels (See Appendix III).

After correlating large-scale, small-scale test results and results obtained by an empirical relationship, Harrison drew the conclusion that the quality levels so established were realistic. Low-cycle fatigue (LCF) implies number of cycles less than 10^4 and stress levels very frequently in excess of the yield strength as well as an appreciable strain at and around the tip of a growing crack. The microstructure and the yield strength in low-cycle fatigue failure mode are generally regarded important. Furthermore, the test methodology is essential in LCF. Reportedly, the effect of 10% slag was drastic in strain-controlled tests, while the same quantity of slag inclusions examined in load-controlled tests was zero (13, 21). An analogous full assessment on porosity is not yet apparent in world publications. Load-controlled tests were done on porosity indicating zero effect for 5% porosity on LCF.

To predict the wave environment for the worldwide mission of a ship is undoubtedly difficult. However, an estimate of the cyclic loading of a surface vessel may be made by defining from an oceanographer's book for the route concerning the representative sea-states over the years. This can be done by using R.M.S. values of wave amplitudes or heights. The configuration of the wave-spectrum, notably the peaks, defines the resultant stress spectrum. There has been some debate whether or not the wave-induced stresses should be treated as purely random. The loading for marine structures is of neither constant amplitude nor constant mean stress. Early in the life of the ship stormy weather may occur inducing levels of stress composed of cyclic, vibratory, mean stresses exceeding the yield strength of the material giving rise to localized yielding at the so-called "hot spots" (stress concentration sites) (22).

6. Environmental Effects

Ships operate in a corrosive environment. The ambient temperature during the worldwide mission of a ship varies. The understanding of corrosion is necessary. In corrosion fatigue, it is important to know the actual level of stress since at very high stresses the crack tip propagates so rapidly that the corrosive medium has no time to react with the fresh crack surface to enhance crack growth. This is because corrosion fatigue is reaction rate limited. "Mechanism of corrosion fatigue is most widely accepted to be related to hydrogen embrittlement" (23). Hydrogen atoms are released at the fatigue crack tip by an electrochemical reaction. The hydrogen atoms are absorbed by the new metal surface, created by the actions of cyclic loading. The continuation of these phenomena results in an atmospheric pressure of hydrogen molecules (gas) in the crack tip inducing hydrogen embrittlement which will increase the crack extension rate. Factors which increase the rate of crack propagation of corrosion-assisted fatigue are:

1. Frequency of cyclic loading.
   For a given stress range, the lower the frequency, the fewer number of cycles required to failure.
2. Corrosion.
3. Dissolved oxygen content of sea water.
4. Ambient temperature.
5. Stress range.
6. pH of the solution (sea water).
7. Stress time wave form.

7. <u>Fatigue</u>

One explanation for such an extensive discussion of fatigue is that, reportedly, the cyclic failure mode is dominant in commercial ships, although the consequences of brittle fracture are usually more serious - at times, catastrophic. Thus, in terms of nature of the consequences of brittle fracture versus fatigue failure, brittle fracture is normally ranked first. Brittle fracture is indicative of through-thickness sudden failure which can transcend the full length of the weldment (24). A survey conducted in Japan between 1950-1969 indicated. that 75% of the “cracks” found in decks and shell plates initiated at toes and roots of fillet welds were caused by structural discontinuities. The failure mode was low-cycle fatigue (3). Other areas of failure were the after structures; those supporting the rudder and the propeller shafts brought on by vibration resulting in high cycle-low stress fatigue.

The solution for fatigue treatment dates back to Palmgren in 1924. Since then, so many hypotheses for fatigue failure modes have surfaced in the world literature that it is rather difficult to keep track of them. A few of the most prominent but simple expressions include Miner's Rule, Foreman's Equation, and Paris' Formula (25).

The worldwide literature survey revealed that structural design details and joint misalignment were the predominant causes of ship failures and not weld defects (22, 26). The survey has also shown that fatigue is the predominant failure mode in commercial ships arising from a multiplicity of causes (26-27). Weld defects as an exclusive cause of fatigue rank very low among the various causes. The ratio of all known causes combined to weld defects is 6:1. This implies that the economic significance of reducing fatigue failure in commercial ships lies in improving structural design details, in minimizing misalignment. A recent survey conducted in the U. S. shipbuilding industry has illustrated that most fatigue failures of ships occur between the second and fourth year in service. Thereafter, frequency of fatigue occurrence decreases (2).

From a fracture mechanics point of view, characterization of fatigue means:

a. Safety from catastrophic failure.
b. Larger defect size permissible.
c. Utilization of cyclic stress range.
d. Defect dimensioning, location and interaction effects.

e. Determination of crack propagation rate.

f. Limit to crack propagation.

g. Selection of confidence level.

h. Quality categorization.

i. Consideration for environment.

The fatigue crack propagation rate analysis should take into account the environmental effects. Owing to the statistical nature of fatigue failure analysis, notably of the simplified version, a safety factor usually taken to be 4 is used. The purpose of evoking safety factors is to take care of the inherent difficulties in determining the exact magnitude of the principal stresses, the complications in defining ambient conditions and the fabrication disparities, as well as manufacturing deviations from design details.

Improvements in fatigue life of welded structures invariably entails methodologies that either reduce stress concentrations, tensile residual stresses or introduce compressive stresses. Amongst such methods one can enlist the following:

- post weld heat treatment (stress relief)
- spot heating
- prior overloading
- local pressing
- weld profile controlling
- TIG or plasma dressing
- peening
- grinding
- quenching

- plastic coating
- cold working to induce surface hardening (viz.,
- compressive stresses)
- application of ductile materials with a lower
- modulus of elasticity in preselected locations of
- a welded structure
- optimizing the method of oxyacetylene cutting

IIW, Commission XIII (on Fatigue Testing) considers the effect of residual stress significant on fatigue. The stress range is the only factor requiring consideration. The mean stress and the R ratio $\left(R = \frac{\sigma_{min}}{\sigma_{max}}\right)$ have negligible effects. The Commisssion advocates large scale testing in the interest of generating useful design data (fatigue curves). The principal concern in the results of fatigue tests has to do with statistical confidence. To this end, Commission XV (on Fundamentals of Design and Fabrication for Welding) encourages the continuation of exchanging welding practice data.

8. Process and Material Variables

The welding process is another important element in the significance of weld discontinuities in that different processes yield different levels of residual stress, which, in turn, influence the significance of weld defects. If the residual stress due to process used and constraint involved is high, a harmless defect can become detrimental to the structure by virtue of excessive residual stress. Existing rules do not make an allowance for this, while fracture mechanics does by way of residual stress inclusion into the stress analysis.

The number of the investigators in the world who have studied the fracture toughness of the heat affected zone (HAZ) in carbon-manganese and alloy steels as well as other metallic materials is stiply too numerous to mention by name. Without intending to display a disrespect to earlier publications, we enlisted in our reference only some of the more recently published papers (28-36). Metallurgically, the HAZ has a complex character for many reasons. We do not intend to go into a detailed elucidation of them, rather to highlight the main facets of the many competing reactions that can take place. In general, the fracture toughness of steels is a function of the steel making process, the welding process used, chemistries, thicknesses, restraint, strain aging, and configurations involved. Furthermore, the resultant toughness of the HAZ will depend on grain structure, amount, shape, type and location of the various constituents that may be present in the microstructure, the residual stresses, carbon content and carbon equivalent. The relevance of cooling rates, phase transformations, austenite → ferrite ($\gamma \rightarrow \alpha$) transition temperature characteristics, hardenability, microsegregation, ferrite morphology, role of specific alloying additions, welding heat input level, number of weld passes, dilution of weld metal, post-weld heat treatment of a particular chemistry of steel under consideration must be recognized. As the plate thickness and the carbon equivalent (CE) increase, the probability for cold cracking (hydrogen embrittlement) increases. One approach normally used in minimizing cold cracking is the raising of the preheat temperature. The search still goes on for enhancing our understanding of the interaction effects of these many phenomena.

From a yielding fracture mechanics point of view, a number of points should be remembered when using C-Mn steels. The transition temperature is influenced by specimen thickness in the wake of altering the micromode of crack propagation (37). The transition from cleavage fracture to ductile failure microvoid-coalescence is brought about by means of a reduction in either the crack length, the crack depth, or the ligament thickness. The K_{IJ} values (equivalent K_{IC} computed from J_{IC}) estimated from J_{IC} values measured in 10 mm thick test specimens are not of necessity equivalent to K_{IC} determined in 100 mm thick test samples. The discrepancy is a result of inequality in stress triaxialities between small and large specimens and the variance in the micromode of fracture initiation. Much of the K_{IC} values in earlier publications were derived from the utilization of small specimens; non-representative of the actual material thickness.

Engineering critical assessment of weld defects is done for the purpose of defining acceptable, harmless discontinuities present in a structure without a sacrifice in product reliability and survivability. The economic harmony between quality control and “fitness-for-purpose” philosophy has received considerable attention in the literature. Some authors have stated that “it becomes necessary in the present climate of economic stringency to examine the possibilities of effecting savings in cost by the acceptance of deliberate reductions in quality standards” (38). If this were true, the fitness-for-purpose philosophy should deserve an automatic rejection. Defect tolerance study must not be construed by anyone to mean "deliberate reductions in quality standards”. Rather, we must emphasize that this new philosophy signifies improvement in both quality and process through better understanding of the interrelationship between process used and concomitant quality.

The degree of departure from the ideal “as-designed” joint by any design criteria is based on some implicit considerations for:

1. Presence of weld defects, and
2. Misalignment of joints

Basar, et al (2) studied the present-day hull construction and inspection procedures to determine the factors leading to and the extent of structural deviations from the ideal, theoretical design in U. S. shipyards. They also investigated the “welding flaws” causing a departure from ideality. Deviations were divided into:

a) “normal deviations experienced”
b) “maximm deviations expected”

Their approach was analogous to the Japanese methodology that had led to “Japanese Shipbuilding Quality Standards--Hull Part”. The Japanese have developed standard tolerances (or standard range) and allowable limits (or tolerance limits) by taking actual measurements of structural deviations in a number of Japanese shipyards developing histograms for measured deviations and from this established:

a) Standard range

b) Tolerance limits for each structural deviation considered

As for deviations in welds (or weld geometry) they looked for:

1. Bead shape including size, undercut, reinforcement.
2. Angular distortion of welding joint.
3. Short bead.
4. Arc strike.
5. Welding done at low ambient temperatures.
6. Weld spatter.

The allowable limits refer to a range beyond the standard tolerances. The allowable limits mean that the product is still acceptable without making modifications to it in the post-process operations (39).

The Japanese quality control standards and practices have been accepted by both the owner/operators and the classification societies. A similar approach was taken and a system developed by Det Norske Veritas (40).

One shipyard radiographed three ships (oil tankers) 100% in order to determine the percentage of weld defects (2). It was found that 15-30% of the welds x-rayed had "some defects". Unfortunately, the report does not identify the type, size and location of weld defects to make a fracture mechanics assessment.

In further reference to fatigue failure, the report states that ". . . cracks or structural failures have been reported as seaway damage or *as* design problems for which reinforcing was the remedy, when in fact the problem might have been misalignment or faulty welding”. During shipbuilding, repair activities were quite varied in completeness and depth among shipyards surveyed.

Some of the observations noted in the report (2) concerning welding are worthy of mention. Fairing by heating in midships and other plating which may be subject to high stresses has to be approved by the surveyor. Examination of weld quality by “radiographic or ultrasonic inspection or both is to be used when the overall soundness of the weld cross-section is to be evaluated. Magnetic particle or dye penetrant inspection or both is to be used when investigating the outer surface of welds or may be used to check back chipped, ground or gouged joints prior to depositing subsequent passes”. The locations and extent of X-ray or UT inspections are indicated in the NDT rules of the American Bureau of Shipping. Specific locations are generally subject to the approval of the attending surveyor.

Very few ships that were reportedly inspected in accordance with previous or current structural and weld tolerance standards have failed in service. Four examples of ship failures were studied and found that misalignment, design details and weld defects caused fatigue cracking. There is no data on “in-service” deviations reported by ship owners, only “recollections”. These recollections appear to indicate that in a number of vessels, structural deficiencies have developed in service, which could be traced back to initial structural deviations (2). Most yards rely on experience and know-how of their own production supervisors as well as that of regulatory body inspectors and owner/operator representatives. The dominant factors in assessing most structural deviations appear to be such abstract opinions as “good marine procedure”, or “pleasing to the eye”. Standards are used as "guides”, which are put to a rigorous testing only in litigation cases (2).

From these observations-it should be evident that formulation of new standards based on an engineering rationale and a fresh re-examination of the system are overdue. Codes and Standards ought not to be regarded as a piece of document reflecting some sort of a status quo, for processes of manufacture do change. Materials improve and their understanding is gradually enhanced. Some standards have been modified to include current understanding of the significance of certain discontinuities, but mostly on a provisional basis (7).

II.B. Critical Observations on World Literature Survey

The subject of weld defect tolerance has received an enormous amount of attention all over the world. Equally apparent from this survey are the following salient observations.

1. There is too much duplication in the international literature on the subject.
2. The fragmentation of efforts are, for the most part, a direct result of insufficient coordination across inter- and intranational boundaries.
3. A systematic research on the influence on weldment behavior of each and every specific weld defect is of relatively recent origin (41). A large portion of the world literature is taken up in treating the relevant fracture mechanics theories and shoring up data to prove the superiority of one theory over another or discussing their comparisons. The time has come to go on beyond this debate.
4. While there is a lot of information and data available in a vast number of international publications encompassing a host of diverse industries, materials, methodologies, processes, specifications and service conditions correlation is extremely cumbersome. The conclusions drawn from specific studies by rigorous definitions are non-identical. This wealth of information must

be synthesized. The British Welding Institute, by having recently instituted its computer-based "Weldasearch" system, brought this problem into a sharp focus (43). "Fatigue Data Bank" for aluminum alloy weldments was recently established at Iowa State University (42). The importance of data compilation has been recognized in many industries *all* over the globe. Our own Marad-sponsored project - among others - attempted to do a synthesis for the U. S. shipbuilding industry.

5. Standardization of methodologies on an international scale is in order, including both the testing technique and the accompanying instrumentation.
6. The exchange of data and information among the countries should be encouraged in a more closely coordinated manner and in accord with a well though-out scheme than had hitherto been done. A Summit Committee might be commissioned for *working* out the details of such a master plan to bring about an early consummation of changes needed in standards.

Modifications of weld acceptance standards should be made according to the needs and requisites of a specific industry. New standards need to recognize the international state of the art of knowledge in welding, materials science, fracture mechanics, design. Due considerations should be given to all relevant aspects of weld acceptance standards through engineering critical assessments.

7. Some classification societies and owner/operator inspectors in the world seemed to have been influenced by a “wait and see what others will do first” attitude. ABS is exploring the possibility of developing guidelines or acceptance standards for locations other than those required and specified in the rules of NDT.
8. Though with measured precautions, we must proceed to take advantage of the fitness-for-purpose philosophy to improve upon existing weld acceptance standards.

11. C. Fracture Mechanics

The fracture behavior of a given metallic material from which a structure is fabricated will be a function of material properties, presence of discontinuities, level of stress acting at the tip of a crack-like discontinuity and the mechanism(s) of crack extension (44).

A general but simple definition of fracture mechanics would be to state that it is a tool to assess the tolerable size of a given discontinuity present in the material or a structure of concern.

The useful attributes of fracture mechanics principles for assessing the significance of weld discontinuities in analyzing metallic material failures is cited abundantly in the scientific literature of the world (1, 4-6, 10-14, 16, 20, 24, 28-29, 37, 44-81). The control, or preferably the elimination, of critical size discontinuities is, of course, not a new concept. What is novel, however, is the elegant methodologies for calculating the critical size of cracks by means of modern fracture mechanics principles.

In general, the following failure modes are recognized:

- brittle fracture
- fatigue
- general yield due to overload of the ligament
- leakage in pressure vessels
- corrosion, erosion-corrosion, stress corrosion fatigue
- instability (buckling)
- creep (rupture)

Many hypotheses for treating the various forms of failure have been developed by the world scientific fraternity, of which linear elastic, elastic-plastic, fatigue and plastic instability have received most attention. Fracture mechanics treatment of fatigue is by far more empirical in nature than either linear elastic or elastic-plastic.

In barest essentials, fracture mechanics entails an understanding of the ductility of materials, or the behavior of a given material in which a defect lies and is under stress. Therefore, fracture mechanics implicitly involves a thorough analysis of:

a. stress
b. Defect
c. Material
d. Environment

a. Stress analysis consists of measuring and calculating all stresses that operate and act at the tip of the defect in question; that is, primary stress across the section thickness, bending stress, secondary stress (thermal and residual) and peak stress (which occurs at stress concentration sites).

b. Nondestructive testing (NDT) of the weldment, including parent material, heat-affected zone and the weld constitutes defect analysis. Defect dimensioning and detection are critically dependent upon NDT. Therefore, the level of confidence in defect analysis is directly related to the NDT selected and the extent of inspection conducted.

c. Material analysis involves destrictive testing of the parent material in order to determine its fracture toughness. Fracture toughness is a measure of the material's resistance to crack propagation.

d. In defining the rate of fatigue crack propagation, an analysis of environmental parameters must also be taken into account. The extent to which environmental parameters influence fatigue crack propagation is reaction rate-limited.

The fracture mode determines which fracture mechanics principle is to be applied. The fracture mode can be judged from the operating stresses (level, type), weldment geometry, environment and material properties. Fracture mechanics principles have been developed for the ensuing failure modes:

- brittle fracture
- elastic-plastic failure (general yield)
- fatigue failure

Fracture mechanics principles are regarded by most experts as reliable in predicting if and when a given weld defect is harmful or innocuous. It is not the intention of this study to give these principles a full treatment herein, rather to present their brief outlines and salient aspects for the sake of relevancy to the underlying theme of the project. The reader who wishes to take a closer look at fracture mechanics theories may consult the various references to this report or any one of the copious publications available on the subject.

Brittle fracture is handled by Linear Elastic Fracture Mechanics (LEFM), giving rise to K_{1c} = critical stress intensity factor. LEFM is used for stress levels below the intrinsic uniaxial yield stress (0. 2% offset) of the material in which the weld discontinuity of interest lays. The stresses must be considered in the vicinity of the crack tip. According to the British Draft Standards (12), if, due to a given discontinuity and principal stresses acting upon it, the stress intensity factor K_1 is equal or less than 0. 7 x K_{1c}, the defect may be regarded as acceptable. LEFM is also used below the ductile-to-brittle transition temperature where plane strain conditions dominate.

The known elastic-plastic fracture mechanics analyses include the Crack Tip Opening Displacement, COD, (δ_c), J-integral, (J_{1c}), plastic-instability (Irwin's theory) and a semi-empirical methodology developed by Kiefner. The original basic concepts have undergone a great deal of improvements and refinements since their respective first appearance in the world literature.

The most widely used elastic-plastic theories include COD and the J-integral methods. The latter (J_{1c}) is used in the USA, whereas the former (δ_c) is preferred in the UK. Both principles - J_{1c} and δ_c - can be applied to the ductile-to-brittle transition region (elastic-plastic zone). Both δ_c and J_{1c} are an index or a measure of fracture toughness of a given material of interest exposed to elastic-plastic conditions (regimes), i.e., non-linear and elastic behavior.

The National Bureau of Standards (60) gives J_{Ic} the following definition: the rate of change of potential energy with respect to crack area and is proportional to the energy required to initiate fracture in a flawed specimen subjected to monotonically increasing loads. The test results in a J-integral curve. The Landes-Begley J-test involves (for ferritic steels and their weldments) the loading of a specimen to a predetermined displacement (crack growth) such that a subcritical crack extension transpires. The specimen is unloaded and subsequently heat treated to tint (oxidize) the crack growth. Thereafter, the specimen is fractured into halves intentionally so as to measure at 3 points equidistant across the specimen thickness, the obtained crack extension. The average crack extension is denoted by Δa. The test is repeated at different test temperatures. For each test, J is computed by the following expression,

$$J = \frac{2A}{Bb}$$

where,

A = area under the load-displacement curve

B = specimen thickness

b = length of untracked ligament in test specimen = W-a

W = test specimen width

a = crack depth in test specimen

From the knowledge of the actual defect size (idealized as depth x length) and the principal (applied) stresses acting at the tip of the defect, an "effective" defect parameter $\bar{a}$ is determined. If $\bar{a} < \bar{a}_m$ (the "tolerable" or "allowable" defect parameter, which is always to be less than a_c, the critical size of defect to cause failure), the discontinuity may be regarded as acceptable. Reasonable methods have been developed to deal with the aspects of defect interaction, locations, planar versus nonplanar defects. Interaction of weld discontinuities is said to raise the stress intensity factor - K - by 20% (12).

"Much of the experimental work on J has concentrated on evaluating K_{Ic} front small specimens" (37).

Under plane strain conditions the equivalence between K and J may be expressed as:

$$K_{Ic} = (J_{Ic}E^1)^{\frac{1}{2}}$$

To measure a valid K_{Ic} the test specimen should have the following dimensions:

$$B, (W-a), a >= 2.5 (K_{Ic}/\sigma_Y)^2$$

The proposed requirements for test specimen size for valid critical J values are:

$$b, (W-a), a >= Y J_{Ic}/\bar{\sigma}$$

where

$\bar{\sigma}$ = flow stress = $(\sigma_Y + \sigma_u)/2$

Y = 25 to 50 (Note: 25 used most often)

σ_Y = yield strength

σ_u = ultimate strength

B = material thickness

W = specimen width

a = crack length

E^1 = Young's modulus, E for plane stress and $E/(1-v^2)$ for plane strain

The analogy between J and δ is given by the expression

$$J = m\sigma_Y\delta$$

where

m = plastic constraint factor ranging from 1-2.

Briefly, the basis of fracture mechanics principles applicable to fatigue is the well-known Paris equation,

$$\frac{da}{dN} = C(\Delta K)^m$$

By taking small increments of fatigue crack growth, starting with an incipient de feet and letting it propagate to an arbitrarily chosen "index of life", also called limit to crack propagation, which by convention is taken to be $N_{crit} = 10^5$ cycles - the rate of fatigue crack growth can be determined. The smaller the increment, the more accurate the calculation. A simplified version of fatigue treatment is based on quality categorization; the so-called "Quality Bands" which are worked out for 97.5 and 99.5% confidence levels. It is an empirical approach founded on a large number of tests.

Because fatigue is the predominant failure mode in ships, the fracture mechanics principles which deal with fatigue are of foremost interest. Quite happily, this means that larger-size defects - especially of the nonplanar type - may be tolerated. The reason being, when extension of a given discontinuity commences, fatigue growth takes place slowly and is usually arrested when it moves out of the stress field. Since in welded structures discontinuities are present and ought to be viewed as cracks, the design for fatigue related applications consists of calculations for crack propagation (22). . LEFM has a limited usefulness in commercial ships since brittle fracture seldom occurs (80). However, due to the catastrophic nature of brittle fracture, it should not be totally ignored.

In welded structures, local yielding can originate either from welding residual stresses which may reach yield stress magnitude and possibly be additive to the applied stress, or it may stem from stress concentrations and may exceed the yield strength of the material (57).

Design curves have been derived by the crack tip opening displacement at specific design temperatures, stress conditions (residual stress inclusive), fracture toughness value of the parent material and the weld. From this information the allowable defect size (parameter = $\bar{a}_{max}$) can be calculated. The actual. test involves weldments with either a natural or an artificial discontinuity. Starting at a certain level of applied stress, said weldment is, then, subjected to increasing levels of applied stress until failure occurs. Then a comparison of the original design stress with the stress at which the weldment with its defect failed is made. If the stress at which failure occurred is less than the design stress, the test is repeated at lower applied stresses until no failure occurs with the same size original defect: hence, the obtainment of $\bar{a}_{max}$ (57).

The attractiveness of fracture mechanics has to do with the fact that it provides a systematic framework for analysis and makes predictions possible for geometries other than those already tested by evoking the so-called geometric factor.

The two basic steps for the calculation of fatigue life are (a) the utilization of S-N curves and (b) the figuring of damage accumulation by means of the simple Paris formula (12, 28, 82-85). Information regarding frequency of loading, stress ranges involved, crack size, shape, and environmental factors are also necessary. The literature survey demonstrates a reasonable agreement on crack propagation as constituting the bulk of the fatigue life in commercial ships involving low strength steel weldments. A graphical illustration of fatigue failure mode is shown in Figure 1 (see Appendix IV).

Normally, crack initiation is important in high strength, brittle materials subjected to high mean stress levels, or in low strength materials exposed to temperatures below their respective ductile-to-brittle transition temperatures.

Once all the components of the local stress field at the tip of a well-defined through-thickness crack have been estimated, the damage rate for repeated-loading can be expressed as a function of the stress intensity factor range by the following expressions:

$$AK = Y\Delta\sigma\sqrt{\pi a} \tag{1}$$

$$\frac{da}{dN} = C(\Delta K)^{m} \tag{2}$$

After combining equations (1) and (2) and integrating from a_i over a_f, the fatigue life becomes:

$$N = \int_{a_i}^{a_f} \frac{da}{C(\Delta K)^m}$$

where,

$\frac{da}{dN}$ = the rate of propagation of a fatigue crack per cycle

$\Delta\sigma$ = applied stress range

a = crack half length

Y = a function of the geometry of the cracked body and the crack size and shape

ΔK = the range of stress intensity factor at the crack tip

C, m = constants for the particular material and testing (environment) conditions

a_i = incipient crack length (size)

a_f = final crack length (size).

N = endurance

A fatigue test to be realistic for commercial ships would involve load spectra of variable amplitude and frequencies for a given mean stress level. To obtain true load spectra, Schutz (25) suggests that the service load records of a ship (if available) be examined statistically.

Fracture toughness is not a material constant until the thickness of the material increases to the point at which plane strain (brittle conditions) develops. The level of confidence in fracture toughness values is critically dependent on the degree of accuracy associated with the determination of:

1. The actual operating conditions;
2. Detection and determination of weld discontinuities;
3. The extent of NDT performed on a given welded structure.

Point (3) involves explicitly the cost of inspection plan required. At this juncture, it might be well to remind ourselves that we not trade off the reduction in the costs of weld repair for the increase in the costs of NDT inspection for the purpose of establishing the maximum level of confidence in predicting structural behavior by fracture mechanics principles.

The application of fracture mechanics principles has been extended to include, in addition to ferrous materials, non-ferrous materials such as aluminum alloys (7, 86-87). Since steel is the primary material for commercial shipbuilding, the weld defect tolerance of non-ferrous alloys will not, therefore, be discussed here.

II.D. Critique of Fracture Mechanics

Like all else, fracture mechanics is not totally immune to criticism. The accuracy of results obtained by fracture mechanics is a direct function of:

1. NDT
2. Stress analysis
3. Fracture toughness test method

Fracture mechanics does not provide a guarantee that detrimental defects may not be present somewhere in the welded structure outside the inspected area. Nor does fracture mechanics tell anything about the level of conformity to specifications and ship-to-ship variability. To attain 100% confidence in the soundness of all ship hull welds would necessitate 100% inspection of full reliability. This would naturally be cost-prohibitive. This suggests that the confidence in the overall integrity of the ship hull must be enhanced by some other sensible ways such as the systems approach, to be discussed later. A debate over artificially introduced defects and generic flaws has produced certain difficulties and some disagreement in terms of acuity, ductility, residual stress state, stress field, microstructure and stress intensity (88).

One of the projects Professor Lundin is currently working on deals with “Characterization and Nature of Discontinuities iii Steel Weld Metals”. In it, he is investigating “localized embrittlement adjacent to weld discontinuities. When this embrittlement occurs, there is a greater possibility of brittle fracture because the effective flaw size is that of the discontinuity plus the embrittled region” (89).

The international literature contains profuse references to the importance of large scale tests for such reasons as including the full scope of the residual stress and simulating bona fide structural and service conditions (12, 18, 45, 88, 90). Furthermore, one of the most frequent criticisms levelled against fracture mechanics is that “it is far from certain to what extent their application can always be relied upon. Thus, there is a strong incentive for carrying out representative tests of large scale in order to include as many factors of uncertainty as possible. This is particularly so with respect to fatigue. Only in this way can the accountability of predictions from smaller scale tests be checked out and, at the same time, give assurance” (90).

The basic principles of fracture mechanics are sound. It is the data acquired for conducting relevant fracture mechanics calculations upon which the accuracy of the predicted values depend. The input is in direct relationship with the outcome. In the strictest of sense, the ship itself is, of course, the only "test sample” of ultimate reliability.

The implication of weld discontinuity assessment on a fitness-for-purpose basis is thorough examination (12). If and when thins is not possible, safety factors are incorporated. Conceptually, fracture mechanics principles mean the obtainment of “safe” results. The degree of this "safety” in the principles is in part a function of the difficulty in assigning definitive values to the terms and constants of the “mathematical formulations”.

There is a need to avoid certain confusing aspects of fracture mechanics such as what constitutes, for example, the actual Critical Crack Opening Displacement (COD). At present, there are at least four different definitions of COD (δ_c),

1. COD at fracture.
2. COD at the sign of first instability.
3. COD at which an arbitrary amount of crack extension occurs.
4. COD at first attainment of the maximum force.

The size of the test specimens should be unified. The published literature speaks of such divergent matters as:

1. Compact tensile specimens.
2. Full-size specimens.
3. Different methods and various extents to which a sharp crack (fatigue pre-crack) may be introduced.
4. Non-unified force sensing devices.
5. Different gauge locations with respect to the crack tip (front); hence the strain response of the gauge will vary.
6. Three-point bend test with various frictional characteristics.
7. Geometric differences.

Including old and new methods for measuring fracture toughness of ductile metals (general yield) that display substantial plasticity (yield) prior to fracture, one finds most commonly four major test methods:

1. COD.
2. J-integral.
3. Instrumented pre-cracked CVN.
4. Standard CVN impact test.

In the literature one finds twelve alternative fracture mechanics methods for treating elastic-plastic failure modes.

The Standard Charpy V-Notch test method cannot be used to estimate allowable failure stress for welds containing discontinuities. However, *empirical* relationships have been developed to do that. But, their reliability has been severely criticized - in part - on the basis that such high loading rates inherent in standard CVN tests are not normal in large, compliance structures (60).

As to which methodology is best suited for describing the actual, in-service behavior of the weldment with a weld defect in it requires extensive testing, which has been in progress all over the world for some time. Although nomenclatures and denotations of terms of fracture mechanics expressions need be standardized, these matters do not exhibit excessive incongruity from publication to publication. However, *even the* most widely recognized fracture mechanics principles could stand a good bit of streamlining to facilitate comprehension.

11. E. Nondestructive Testing

The relationship between NDT and fracture mechanics is very important. Weld discontinuities constitute the center of NDT. However, the limitations of present day nondestructive testing methods must be taken into account (12, 91).

The reading and interpretation of radiographic films can be very cumbersome. There can be discrepancies in estimating defect lengths for radiographic images. Defect depth measurements by X-ray is more uncertain than length dimensioning (60). The latter is sensitive to film density, film processing, radiographic procedure such as X-ray energy used, variations in material or weld thickness.

Nondestructive weld inspection methods employed in the commercial shipbuilding industry include (1) visual, (2) magnetic particle, (3) radiography, (4) ultrasonic testing, (5) dye penetrant, and (6) eddy current. The guide for nondestructive testing of non-butt welds in commercial ships does not contain definite acceptance criteria for weld discontinuities. The so-called ASTM “Reference Radiographs” present several levels of severity for each discontinuity. They are useful to assist in discontinuity identification; but, the maximum permissible severity must depend on the structure.

A common recognition of present shipbuilding weld inspection methods is that they are rather arbitrary: visual inspection more so than radiography or ultrasonic testing.

Most non-butt welds in commercial. surface vessels are deemed non-critical. Thus, they are not full penetration, rather, they are usually simple fillet welds. Since an incomplete penetration is more severe than either slag inclusions or porosity, therefore, inspection for an internal (buried) defect is unwarranted and in general not required. These joints, by acceptable company quality control practices, are merely required to meet good workmanship. "Good workmanship" is an inexact term. The type of inspection these joints are afforded is visual only and may be supplemented by the utilization of a gauge. Common failure modes, when failures occur in non-butt welds, have reportedly been lamellar tearing or failure at the toe of the fillet weld.

Besides the butt joint, the American Welding Society recognizes four types of weld joints, namely corner, Tee, "X", and lap joint. "The selection of a nondestructive test method should be based upon the need to detect certain types of weld defects which are acceptable either because of service requirements or company standards". This implies *a* great deal of arbitrariness or subjectivity.

The guides set up for NDT of ordinary-, medium-, and high-strength low-alloy steel butt joint weldments in ship hull structures constitute nothing more than suggestions with regard to acceptable size and/or distribution of weld discontinuities (92). "It is not the object of this document to designate the location or extent of the inspection on a ship's hull, but rather to provide guides for the interpretation of such tests by qualified personnel. It is expected that only those discontinuities need be removed and repaired as necessary to render the weld acceptable in accordance with the applicable guides herein". This document states the length requirement of the appropriate defect, but makes no mention of depth requirements for the same discontinuity irrespective of method used. It is generally agreed that defect depth estimates from field radiographs have inaccuracies (45). Weld acceptance standards for X-ray and UT inspection of commercial ship hulls are specified by ABS (93).

Publications on the accuracy of ultrasonic testing show controversy. Some of the international literature claims good sensitivity for UT (94-96), while others indicate inadequate levels of accuracy for purposes of fracture mechanics analysis (77, 97-102). More important perhaps is the fact that tight cracks or crack-like discontinuities in certain situations are well-nigh impossible to detect. Improvements in these methodologies are both desired and needed. Some may interpret this to mean that more inspection by ever more sophistication is an answer to our problems. This, of course, would entail increasing costs in both inspection and fabrication. Of the various NDT methods, the ultrasonic technique has gone through one of the most impressive development stages since 1965 in being able to detect more as well as finer defects than some other methods. As a result, UT has achieved quite a bit of prominence, surely more in certain industries than in others.

This increased application of UT - interestingly enough - has brought about a greater demand for new weld discontinuity acceptance standards (103). An explanation for this seeming paradox is that as NDT techniques improve, undesirable pressures develop to generate more rigorous acceptance standards. One must keep in mind that there has to be a healthy balance between desirability required by a given code and attendant costs. Moreover, the relationship between inspection and product quality is not necessarily proportional.

The international literature calls the nondestructive inspection methods by the following expressions:

- Nondestructive Testing (NDT)
- Nondestructive Examination (NDE)
- Nondestructive Inspection (NDI)

Nondestructive weld inspection techniques will no doubt go on improving, so as to enable us to detect both more and smaller defects than is possible with present-day techniques. This fact carries in it the daunting prospect of an incessant rise in weld repair costs that we obviously cannot afford. That is precisely why the significance of weld discontinuities must be well understood. It is for this reason that we need to adapt fracture mechanics principles to the engineering critical assessment of weld defects. Through the application of these principles, we are able to distinguish from a fatigue and a fracture control standpoint, between innocuous and deleterious weld defects present in a structure; hence, avoidance of superfluous expense based on a calculated conviction.

II. F. Present Shipbuilding Codes

Weldments in ship hulls are by and large randomly checked. Typically, less than 5% of all ship hull welds are inspected, volumetrically. Consequently, there can be no satisfactory guarantee that all the welds would meet acceptance standards. Guarantee in such a QC system can only stem from historical precedents. Therein lies a good deal of the history of existing shipbuilding weld acceptance standards having evolved through experience (104). The main objective of quality control standards for commercial ship construction is the prevention of fatigue, brittle fracture and "cracking". Cracking is a vague term often used to imply cold cracking, lamellar tearing, hot cracking, solidification cracking, hydrogen embrittlement, cracking caused by collision and so on (3, 26).

The present criteria for discontinuity acceptance under repeated and intensive scrutiny of the last two decades have been found unduly conservative requiring excessive repairs (4, 105). Current ABS rules do not address the situation when a combination of problems coexist, namely misalignment, allowable defect size and residual stress.

Future standards formulated upon fracture mechanics principles are expected to be less conservative, tailored specifically for the shipbuilding industry and optimized for the purpose of minimizing unwarranted weld repair.

The practice of quality control of welds in American commercial shipyards is guided by American Bureau of Shipping Rules, U. S. Coast Guard Standards, owner/operator requirements and the individual shipyard's own traditional quality control criteria. The preponderant NDT techniques in shipbuilding are visual and radiographic. Ultrasonic, magnetic particle and dye penetrant tests are also often used, but *to* a lesser extent in general than the aforementioned two methods.

Visual inspection is routinely performed during the entire course of the erection of a ship. The number of x-rays taken of the finished ship is governed by the rules of relevant classification societies and is determined by a pertinent equation formulated in accordance with the size of the ship in question. Usually shipyards do more inspection than is required by relevant code making bodies. On the other hand, some owner/operators have been known to impose more rigid quality control requirements than either the classification societies or the shipyard itself.

The conception of existing codes and standards that are still the rule of the shipbuilding industry in the United States are essentially rooted in the capabilities and limitations of the available NDT techniques at the time of writing said standards. Today's NDTs are better. However, that should not mean that codes should commensurately be made more restrictive just because we are able to detect smaller size discontinuities more accurately than before. The acceptability of a given type and size of defect by the rules of governing codes should be determined not by the momentary ability of NDTs but by engineering principles, as to whether or not a discontinuity is harmful to the integrity of the ship or to that of its components. Existing codes are a carry-over from more primitive engineering eras in terms of type of materials, processes and level of understanding in the two, and adaptation of one country's standards by another. As Dr. Lundin states, "Enough evidence exists to show that the traditional importance ascribed to certain discontinuities required to be weld repaired has gotten over the years grossly blown out of proportion and as such it serves to direct attention away from other but far more important considerations: e.g., design, implementation". This ought not to be construed to imply that welds are never at fault. Welds have been known to be a source of failure or initiation sites for same. However, welds by themselves - reportedly - very seldom precipitated structural failures. Lancaster (106) analyzed pressure vessel failure in the United Kingdom and Europe and found only 1 out of 29 explosions shown to be caused by a weld discontinuity, others by operational errors. Lancaster concluded that failure risks decreased with improvements in:

- Material
- Design
- Construction

Week (78, 107) delivered perhaps one of the most poignant criticisms on existing weld acceptance standards. He drew a parallel between present codes and "interminable discussions of totally fictitious problems in a fog of taboos whose origin is lost in ancient engineering history". Dr. Weck further observed that the very nature of standards serves as a resistance to modifications. In the aggregate, however, "critics of codes and standards are not disruptive detractors advocating code and standard abolition” (1). Nor do they suggest to disregard the knowledge gained from previous experience with quality known to have produced satisfactory service results. In this sense, present codes do possess rationale albeit in the direction of excessive caution.

Taking a critical stance, one can look at a weld as a metallurgical discontinuity in the structural continuum. The question, however, is it detrimental or totally innocuous? The true answer to the latter is by far more important than the elucidation of the former from both a fatigue and fracture control, and an academic point of view of the weldment. Some of the code making bodies have to some extent incorporated changes to standards on the basis of growing experience, understanding and handling of fracture mechanics. Nevertheless, they constitute no more than an optional alternative. In this regard, one can exemplify ASME Section III and XI, Appendix G and A. Another similar effort is the International Institute of Welding Documents V-438-70/OE and V-416-69/OE, which are welding design rules incorporating discontinuity levels permitted in codes and standards of many countries. IIW DOC. V-419-69/OE is “Acceptance Levels for Discontinuities in Fusion Welds” based on fitness-for-purpose philosophy. They are for fatigue failure mode. For the brittle fracture mode the British Welding Institute proposed IIW DOC. X-679-72 and X-749-74, but they are not yet approved for application by IIW.

Dr. Leide of Kockums Shipyard in his private correspondence to this author writes, “I have been engaged in the work behind a proposed Swedish standard for the assessments of weld defects and also been involved in a suggested shipyard standard which is used in our yard . . . in cooperation with the classification surveyors in our yard. As to Det Norske Veritas, their investigation is not published”. The results of the investigation conducted by DNV on the assessment of weld discontinuities were sent to experts for comments but no changes in existing standards have so far been decided upon, according to Dr. Leide.

There is no published evidence in the literature surveyed to indicate that as of to date fracture mechanics would have attained recognition beyond recommnendation, proposal, draft, option stage or documentation.

Welding handbooks recommend a nominal reinforcement of l/16” (1.6 mm) above flush. Any more reinforcement is regarded as simply increasing the cost of welding and leads to problems when high fatigue strength is required due to the stress concentration role of toe defects formed at the edge of reinforcements. Weld undercut allowed in most U. S. shipyards is 1/32” (0.88 mm) or less when the applied stress is parallel to the weld. More effort is expended in eliminating undercuts when the applied load is normal to the weld. Undercut can be caused by dimples in the steel plate. The tolerance range for such surface pits is 1/64” - 1/8” (0.4-3.2 mm).

The Ship Structure Committee “guides” (92, 108) for non-destructive inspection of ship hull welds can be contested in light of more recent studies. The "interpretation standards" state that "all weld surfaces containing cracks, porosity and lack of fusion are unacceptable". The permissible discontinuity length is set up on the basis of plate thickness from 0.5" - 2.0" (12.7 -50.8 mm) per 6" (152.4 mm) weld length. Over 2.0" (50.8 mm) the permissible length is constant for LOF/LOP using radiography. Ultrasonic testing is used for plate thicknesses greater than 0.5" (12.7 mm). The number of check points in the 0.6L midship section is defined by the following formula:

$$n = \frac{L(B+D)}{500} \quad \text{inch units}$$

where,

L = length of vessel between perpendiculars

B = breadth

D = depth

At selected weld intersections, a minimum of 10" (254 mm) of weld, measured from the intersection in each direction transverse to the axis of the vessel is to be inspected. Areas outside the 0.6L midship section are randomly selected at the discretion of the surveyor; usually intersections of butts and seams in the main deck, in the vicinity of breaks in the super-structure, various field erection and suspected problem areas. Class A acceptance criteria are applied to critical locations in the 0.6L midship section for surface vessels of 500 ft (150 m) and over. Class B is applied to all other locations and applica-tions except where Class A is specified due to special hull material or design requirements.

Again, the acceptance criteria for discontinuity indications by UT are set up in part on the basis of plate thickness. over 2“t (50.8 mm), the greater the plate thickness, the longer the permissible length of discontinuity indications with respect to the Amplitude Reject Level (ARL). Many investigations (6, 24, 28, 52-55, 65, 69, 81) showed the significance of plate thickness on the overall toughness level and failure mode. In terms of weld defects, the general direction is that as the plate thickness increases the tolerable discontinuity size decreases. In transverse non-load carrying fillet welds with a given initial toe defect the fatigue life tends to decrease rapidly with increasing plate thickness over the range of steel plate thicknesses utilized most commonly in engineering weldments (65, 81). This is often referred to as “size effect”.

11. G. Current Understanding of Weld Repair

Because the heart of the Defect Tolerance Study is weld repair, one must have a good appreciation for its influence on the resultant changes in the weldment.

The effects of weld repair can be harmful irrespective of material and welding process utilized. There are numerous well-known examples, published or otherwise, to the effect that weld repair very often turned out to be more deleterious than the original defect in terms of weldment survivability due to a number of phenomena.

Manifestations of these harmful effects include:

1. Increased residual stress and distortion;
2. Introduction of new defects;
3. Microstructure, material toughness degradation;
4. Aggravation or extension of pre-existing defects that went undetected during the original inspection.

Weldment and weld discontinuity degradation may be manifested in grain growth, embrittlement, thermal straining of cracks. The British Draft (12) in its preamble states, "It should be appreciated that the unsatisfactory repair of innocuous defects could result in the substitution of more harmful and/or less readily detectable defects”.

Tenge (109) conducted fracture mechanics tests to determine the values of δ_c for the weld metal, the fusion line and 1, 2 mm from the fusion line in the original weld as well as after weld repair. Size of the COD specimen was 12 x 38 mm fatigue notched to 19 mm depth and tested at O°c. The basic material was C-Mn steel (.26%C and 1.35% Mn). He found that the lowest ðc values obtained were for the repaired weld. Furthermore, the same weld repair bad "fish eyes" defect (a form of porosity) due to the use of cellulosic electrodes. These electrodes are noted for high hydrogen contents.

"If the fusion between successive layers of weld bead is marginal in the original weld, the repair weld may cause these layers to separate. This condition referred to as cold laps is found during the final UT." Collins and Black reported the following additional types of cracking resulting from repair welding: crack in repair weld due to zinc contamination, a massive repair weld inducing crack in the base plate (110). They recommend that final UT inspection of heavy welded structures be performed after erection, since crack-like indications may open up and can be detected much more readily after installation.

Cracks detected in electroslag welded highway bridge girders (Interstate 79 bridge in Pittsburgh, Pennsylvania) have been given considerable publicity. Professor Pense found a high incidence of weld repairs in these girders (111). Residual stresses induced extension of pre-existing cracks or crack-like defects adjacent to weld repairs. This investigation revealed further discontinuities in the weld repair such as slag and porosity. Lauriente said, "Weld repairs made to electroslag welds are particularly vulnerable to failure." (112).

In Polaris and Minuteman rocket chambers, weld repair led to defects consisting of a coarse, columnar grain structure, inclusions and low melting point eutectic (29, Irwin). In such microstructures, the interracial bond is typically very weak. This kind of defect could not be detected by NDT. When the rocket chamber was subjected to a hydrostatic test, the chamber flew apart. The original welding process used was submerged-arc welding. The fix for this problem was a change from submerged-arc welding to multiple-pass TIG welding in order to obtain a better toughness level. Later, the steel was also changed to vacuum remelted maraging steel. The vacuum remelting steel making practice is known to reduce inclusion content in the steel.

These examples serve to illustrate some important observations. Unfortunately, over the years a somewhat indiscriminate application of a rather erroneous philosophy as well as attitude has been developed toward the question of what constitutes a critical weld defect and what will indeed be the consequence of a repair.

Weld repair should not be viewed as an ipso facto improvement. Other often overlooked aspects of weld repair are the additional welding personnel required, late delivery, interruption of work schedule, loss of good will, and occupation of berth space (4, 70). Since there is a short supply of skilled welders, reduction in weld repair guided by rational engineering principles would help alleviate this problem. Moreover, weld repair often involves not just welders exclusively but persons from other trades and disciplines as well. In toto, it behooves all of us to put our contemporary understandings on the full implications of weld repair in better perspective than they might have been before.

II.G.1 The Role of Residual Stresses in Fatigue and Fracture

A general physical meaning of residual stresses is that they come from constraint and weld repair (113). Immediately after fabrication, residual stresses may attain yield strength magnitudes. Upon any subsequent loading, which brings about a stress of the same sign, the weldment may undergo some yielding to the extent that on the removal of the load the remaining residual stress is below the yield value (114). Such a relaxation of the residual stress has a control on fatigue crack growth.

A retardation of fatigue crack-growth rate in weldments was attributed to the presence of compressive residual stresses arising from welding (115). Kapadia analyzed this in terms of a stress-intensity-factor range suppression concept, whereby the applied stress-intensity-factor range was decreased to some lower "effective" value. While the retardation was more pronounced at low ΔK values, the beneficial effect of compressive residual stresses on fatigue crack propagation seemed to be of a variable nature. In light of the findings by Kapadia and many others (1, 53, 115) on the adverse effects of weld repair it is necessary to make a distinction between the tensile and the compressive components of residual stresses that are operative in the vicinity of a defect in question.

An oil storage tank in England in 1953, under static loading conditions and no internal pressure of significance, collapsed overnight (53). “The conditions preceding fracture were quiescent at 5°C, with a known static hoop stress of 11 ksi tension. All slow loading tests of the parent material and weld metal showed ductile fracture at 5°C without notches, but cleavage fracture at the ultimate strength of the material (60 ksi) if provided with sharp machined notches. In order to demonstrate low applied stress cleavage fracture at 5°C, it was necessary to incorporate the following conditions:

1. Full material thickness;
2. Minimum specimen width of 3 feet;
3. The weld in the direction of tension with its tensile residual stress system;
4. A machined notch in the weld preparation”.

The three principal conclusions Dr. Wells arrived at from this experience were that:

a. “Weld residual stresses associated with appropriately oriented defects of sufficient size can induce brittle fractures without substantial help from external loadings; such fractures are usually arrested at short lengths.
b. “Through fractures at low applied stresses can occur from small weld defects placed in fields of tensile residual stress.
c. “Low stress fractures are correspondingly more rare in welded structures which are first thermally or

mechanically stress relieved and may be discounted with steels of low yield strength."

The occurrence of residual stress and HAZ in welds is simultaneous in a degraded microstructure. In situations when the heat-affected zone is very narrow and the material is in the tamperature regime of the upper shelf or above, the crack is arrested after it has propagated out of the inducing stress field or the undesirable microstructure region. The tensile residual stress is detrimental to brittle (unstable) fracture conditions, (e.g., below the ductile-to-brittle transition temperature). If crack initiation is preceded by a sizeable plastic flow, the effect of tensile residual stress is negated (1). All the electric-arc welding processes used in shipbuilding result in high tensile residual stresses, which are at or near the yield point in the weldment and the substrate adjacent to it. In the initial stages of fatigue crack propagation in an as-welded structure such as a ship hull, most of the fatigue life takes place in regions of high tensile residual stress. Under cyclic loading conditions the steel at or near the incipient defect will be subjected to a fully effective cyclic stress even in the event of stress reversal. This accounts for the fact that stress range alone governs fatigue behavior of welded joints. The stress ratio is not important in describing the fatigue strength of weldments, because the maximum stress inducing fatigue crack (initiation and propagation) is almost always at the yield point.

The most common practice to reduce the influence of residual stress is to use thermal stress relief. A number of authors caution against the use of “mechanical stress relieving treatment” {more recently called vibratory stress relief (116)}, lest damage occur at roots of discontinuities and geometrical notches (79).

II.H. Statistical Analysis of Shipbuilding Q.C. Data

Present statistical sampling techniques of NDT in most manufacturing industries are for the most part unsound and lack quantitative information on the distribution of individual defects (22). The same is true about the shipbuilding industry. Until this situation is remedied, the statistical methodology cannot be used with high enough reliability for establishing weld acceptance standards.

Notwithstanding, an effort was made to solicit information on quality control data with primary considerations for commercial ship hull construction. Incidental to this effort was the collection of some information regarding naval ship construction. The plan involved discussions with knowledgeable representatives of four of the key U. S. shipbuilding companies. A careful analysis of the information showed a rather interesting picture on the present state of the art of quality control in the U. S. shipbuilding industry.

An extremely high degree of commonality can be observed in the information supplied. What are these commonalities? Weld intersections selected randomly in the midsection of the ship are considered as the most critical area inspected mostly by x-ray. In addition to radiography, welds in general may also be examined by other NDT methods such as ultrasonic, liquid penetrant, magnetic particle, eddy current and visual means. The choice of NDT method utilized is governed by the appropriate requirement(s). Visual inspection can be anti most commonly is as much as 100% of all welds made. The dominant rule applied to the inspection of commercial ship hull welds is that of the American Bureau of Shipping. The range of weld discontinuities found in visually and x-ray inspected welds has been reported to be 2-25% and 5-20%, respectively. On ultrasonic and magnetic particle inspection three yards provided information: 1-14% and 1%, respectively. Let us remember that less than 5% of all commercial hull welds are inspected “volumetrically”. While we do not know with absolute certainty, it might be reasonable to assume that the non-inspected hull welds would have the same amount of weld discontinuities present.

Of all the weld discontinuities so detected, approximately 25-50% is weld repaired. The estimated dollar value of this amount of weld repair activity ranges from $0.6 million to well in excess of $1.0 million/ship. If - in addition to commercial ships - one considers naval ships, the cost of weld repair can reportedly be as much as several million dollars. It is generally believed that, of the reported expenditures for weld repair, 50-100% is deemed unnecessary. This would result in savings ranging from:

$0.3-$1.0 million plus

Those who believe that 100% of the repairs arising from non-destructive inspections are superfluous explain their argument for it on the basis of statistical probability. This is because volumetric inspections are themselves only performed on say 5% of welds. Thus, even if the ship does fail from a weld discontinuity, it is 20 times more likely to be from such a discontinuity in a weld which was not inspected than from one which was, even if in the latter a deliberate decision was taken to allow the discontinuity to remain. The preponderance of weld repair activity involves mostly slag inclusions and, then, to a much lesser extent porosity, LOF/LOP and undercuts. The latter is usually associated with fillet welds inspected mostly by visual means. The type of weld discontinuities found in welds is primarily (a) process and (b) NDT method-related.

A generally held opinion in welding industries today is that “small porosity, slag inclusions should not be weld repaired”. The acceptance of these weld discontinuities should be judged by design criteria based on the fitness-for-purpose philosophy (see Appendix III). Intersections of butt- and seam welds in shells, decks, longitudinal stiffener butts, box girder weldments, sheer strake, heavy castings, pipes, and confined areas are regarded as most troublesome locations on a given ship likely to require weld defect repair after inspection by any NDT method. The accuracy of present NDT methods used in commercial shipbuilding is considered adequate.

While weld defects have been known to cause an occasional failure, design details (joint geometry, stress risers), misalignment are, on the basis of reports, the principal contributors to ship failures. The predominant failure mode is fatigue, though brittle fracture has also been observed in ships.

The discussion on the Quality Control Systems Loop gave rise to an overwhelming approval by experts representing the four major U. S. shipyards. Furthermore, it was learned that Navy ships do in general undergo more extensive inspection involving more NDT methods than their commercial counterparts. There is, however, no data available which could be analyzed to determine the usefulness of more extensive inspection methodology in terms of a reduced failure occurrence in Navy vessels relative to commercial ships.

The amount of weld repair done during shipbuilding can be categorized along various lines:

1. Weld repair in the shop;
2. Weld repair on the shipways;
3. Weld repair due to weld defects exclusively;
4. Weld repair due to weld defects, poor fit up, and “cosmetic” reasons;
5. Weld repair according to the welding process used;
6. Weld repair on the basis of linear feet inspected;
7. Weld repair owing to random-occurrence of weld discontinuities.

It goes without saying that the seven categorizations would yield as many different results. If one were to consider all repairs induced by all causes one would find the ratios of man hours per linear feet of weld in the shop and on the shipways to be 0.021 hr/ft (1.3 min/ft) and 0.195 hr/ft (11.7 min/ft), respectively. These values were obtained from data at one shipyard. The difference is approximately a factor of 8.

A more rigorous examination of available data and literature information shows that the occurrence of defect types and their relative quantities depend on:

1. Weld process used;
2. Inspection method applied;
3. Type of weld made;
4. Joint fit up.

The ranking of weld defects by frequency per linear feet of radiographic inspection is as follows:

1. Slag;
2. LOF/LOP;
3. Porosity.

The ranking of defects change when expressed on the basis of random occurrence, namely;

1. Slag;
2. Porosity;
3. LOF/LOP.

The reasons for the change in the relative significance of defect occurrence are twofold. Lack of fusion and lack of penetration are automatic weld process related discontinuities. Thus, when they occur during automatic welding they are not detected until the weld is completed. Consequently, LOF/LOP can constitute a relatively high percentage of the detected discontinuities. Detection of instantaneous defect formation during welding would necessitate instrumentation which makes use of, for instance, acoustic-emission principles.

In terms of manual versus semi- or full-automatic welding processes, and taking into account the total amount of weld discontinuities found in welds inspected by the various NDT methods in shipbuilding, the ranking of specific weld defects is as follows:

(I) DETECTION BY X-RAY

(total amount: 5-20%)

(A) Manual Welding			(B) Automatic Welding		
1.	Slag	35-80%	1.	LOF/LOP	30-60%
2.	Porosity	10-20%	2.	Cracks at ends of butts	19-25%
3.	LOF/LOP	8-20%	3.	Slag	5-25%
4.	Cracks	l-l0%	4.	Porosity	5-15%

(II) DETECTION BY UT

(total amount: 1-14%)

(A) Manual Welding			(B) Automatic Welding		
1.	S l a g	50-65%	1.	LOF/LOP	60%
2.	LOF/LOP	20-30%	2.	Slag	20-35%
3.	Porosity	5-30%	3.	Porosity	5-20%

(III) DETECTION BY VISUAL MEANS

(total amount: 2-25%)

(A) Manual Welding			(B) Automatic Welding
l.	Undercut	15-80%	No data available
2.	Surface porosity	5-20%	
3.	Undesirable weld profile	2-15%	
4.	Cracks at craters	l-l0%	

It is important to point out that the total amount of the discontinuity types indicated above for each NDT method is typically much less in automatic than in manual welding.

All else being equal, the quantity of weld discontinuities detected is in part a reflection on the level of a general workmanship and working environment in a given shipyard. A case in point is the reported results classified on the basis of shop versus shipways determined by means of visual examination and magnetic particles.

shop

TYPE	%
Undercut	15-30
Porosity	4-30
Undesirable weld profile	2-10
Cracks	2-10

Shipways

TYPE	%
Undercut	30-80
Porosity	10-30
Undesirable weld profile	5-15
Cracks	5-10

If one, now, analyzes the available data strictly on the grounds of manual welding vis-a-vis automatic welding an ensuing picture of weld discontinuity ranking is attained.

Manual Welding

1. Slag
2. Porosity
3. Undercut
4. LOF/LOP
5. Undesirable weld profile
6. Crack

Automatic Welding

1. LOF/LOP
2. Slag
3. Crack
4. Porosity

Undesirable weld profile includes convexity, weld surface roughness, uneven welds. The most frequent weld discontinuities observed in U. S. shipyards by welding process were reported to be as follows:

Shielded Metal-Arc Welding . . . . Slag
Submerged-Arc Welding ... . Slag (and/or LOF/LOP)
Flux-Cored Arc Welding .... Slag (and/or porosity)
Gas Metal-Arc Welding .... Porosity
Gas Tungsten-Arc Welding . . . . . Porosity

An overall ranking in terms of significance of occurrence of weld discontinuities in the U. S. commercial shipbuilding

1. Slag;
2. LOF/LOP;
3. Porosity;
4. Undercut;
5. Crack.

This ranking is established on the basis of weighted averages. It is interesting to note that a replacement of or a reduction in the utilization of the shielded metal arc process by automatic welding processes would in itself signal a drastic decrease in slag inclusions. This would bring about a twofold benefit to American shipyards: (1) increase in weld productivity and (2) a substantial paring in weld repair costs. Interestingly enough, the relationship between the cost savings realized from the dramatic reduction in slag inclusions through the introduction of automatic welding processes is nonlinear in terms of fabrication shops versus shipways. The reason is that the cost of weld repair for the same slag inclusion is eight (8) times as high on the erection site as on the floor of the fabrication shop. Hence, the economic benefits arising from reduction of slag inclusions through the same automatic welding process used on the shipways as in the fabrication shop were considerably greater.

II.H.1 The Significance of Structural Details

A structural details failure analysis was conducted on 50 ships of seven different classes, and various displacements built by domestic and foreign shipyards (26).

The age of the vessels ranged from 4-30 years. The details were grouped into 12 structural families. The total number of details observed were 490,210 of which 3,307 showed “failures” amounting to 0.7% failure occurrence. As expected, 82% of the less than 1% failure occurrence in 50 ships of the total number of failures were located in the midship section and primarily in the structure next to the side shell. Of the remaining 18% observed failures, 10% were found forward and 8% aft of the cargo spaces. The report makes no attempt to characterize the “cracks” in terms of failure mode to be useful for selecting the pertinent fracture mechanics principles so as to assess the significance of weld defects. Failure mode in this report can mean cracks, buckles, cracks and buckles, and twisted/distorted; each mode identified with numbers. Of all the 3,307 failures, 221 cases of "crack” failure modes are reported; hence a 6.6% occurrence rate of the 0.7% overall failure rate. Of the 221 cracks, only 34 were caused exclusively by “welding”. This means that 15.3%

Of the "cracks" were weld related and the remaining 84.7% induced by other causes, specifically:

CAUSE	OCCURRENCE PERCENTAGE
Design	36
Heavy seas	26
Fabrication/workmanship	11
Combined tension and shear	11
Collision	10
Shear	10
Neglect	9
Questionable	8
Misuse/Abuse	4
Tension	3

The reason for the "occurrence percentage" exceeding 100% is because there were multiple causes reported for the preponderance of cracks. This was due to difficulties as stated by the authors, in the precise definition of a single cause in several failures found.

If one evaluates the 221 cracks by the reasons given on the basis of (a) cracks caused by a combination of factors exclusive of welding and (b) the same but welding inclusive, one finds 59 cracks (26.5%) for case (a) and 24 cracks (10.9%) for case (b).

While it was rather cumbersome to analyze the data from a weld discontinuity point of view, a reasonable overall ranking of "crack" causes may be as follows:

1. Structural design;
2. Combination of factors <u>exclusive</u> of welding;
3. Heavy seas;
4. Welding;
5. Fabrication/workmanship;
6. Combined tension and shear;
7. Combination of factors inclusive of welding;
8. Collision;
9. Shear;
10. Neglect;
11. Questionable;
12. Misuse/abuse;
13. Tension.

Therefore, from a fatigue and fracture control standpoint of a ship in-service, improvements in the structural design details are considerably more important than an enhancement in the inspection of welds and welding processes currently applied in U. S. shipyards. In fact, the information presented in this report suggests that there is a substantial incentive to selectively relax existing weld acceptance standards.

II.I. Case History of Alyeska Oil Pipeline

The principles of fracture mechanics have in recent years been tested extensively. The most notable example in this regard is the Trans-Alaska Oil Pipeline girth welds. The Alyeska crude oil pipeline project represents - on a giant scale - the world's first testimonial to the applicability of fracture mechanics principles as a tool to assess the significance of weld defects in girth welds. Because fracture mechanics principles were successful in demonstrating the overconservative nature of an existing code and made a change in the code possible, it *was* thought appropriate to devote a chapter to the discussion of this important case history. Moreover, the very essence of this famous case history was deemed apropos of the objective of this project.

The original construction code applied to the pipeline was API-1104 and the defect acceptance levels in it were established to maintain a certain level of workmanship. But, it bore no relationship to the performance of the pipeline in service (57). The audit of 30,000 welds revealed discontinuities larger in size than what was allowed by the relevant code in some 2,955 girth welds. The extensive tests conducted by the British Welding Institute, Cranfield Institute of Technology, the American National Bureau of Standards and Southwest Research Institute showed that the weld defects and arc burns in question "under the conditions of best estimates for criticality" required no weld repair.

Among others, this case history included the testing of three types of arc strikes, namely,

"touch" (arc time = 0.056 second)

"strike" (arc time = 0.158 second)

"drag" (electrode dragged across the full width of the specimen at mid length)

"Touch" involving the lowest heat input gave the highest no break transition temperature. This was presumably due to a high local hardness giving rise to a low local toughness. However, all three types of arc strikes yielded no break transition temperature far below the minimum conceivable steel temperature in Alaska (117). The chemistry of the pipeline steel manufactured by Nippon Kokan KK is shown in Table I (l17).

Hydrogen induced stress corrosion cracking (SCC) can occur at arc strikes under severe environmental, above-yield-stress and high material hardness conditions. When the Alaskan pipeline material was softer than 310 HV 2½ (=31 R_c), no SCC was observed (118). Therefore, SCC at arc strikes would most likely terminate in HAZ. SCC, even under the most severe environmental and stress conditions, can occur only in materials whose hardness exceeds 250 HV (118). So, crack propagation by stress corrosion mechanism into the parent steel is believed to be extremely improbable. No stress corrosion was discovered in the weld metal of Alaskan pipeline steel even in the presence of a weld discontinuity of applied stresses above yield and under ambient conditions expected on a historical basis in Alaska (118).

"Irregularities" detected on radiographs included:

1. LOF and LOP;
2. Slag inclusions;
3. Porosity;
4. Cracks;
5. Gas pockets;
6. Hollow weld beads;
7. Burn-through.

The largest number of repairs required by Code involved gas pockets located mostly at the bottom of the pipe where welders ended their weld (87). All these "irregularities" can be categorized using fracture mechanics terminologies as planar, non-planar defects and arc burns (45). The approach taken to assess whether these discontinuities are deleterious or innocuous assumed worst-case conditions. Specifically, all flaws were considered as surface cracks. Furthermore, calculations were carried out on the basis of minimum material toughness, maximum stress arising from high hoop and tensile residual stress, pipeline loading and pressure, earthquake, worst-case fatigue, most adverse service environment, corrosivity, and temperature. The crack growth rate was assessed under both cyclic and sustained load conditions. The net conclusion according to the fitness-for-purpose criteria was that larger flaws can be allowed than the API Standard 1104 had permitted. So, DOT granted waivers for compliance with API-1104 and DOT accepted the principles of using a Yielding Fracture Mechanics analysis to derive defect acceptance levels in a large pipeline project (57, 60, 61, 119). Again, the uncertainties were taken care of by assuming “worst-case-conditions” and by including safety factors. The net effect of such assumptions is a notable conservatism in the calculations. Nonetheless, the conclusion proved that the standards applied to the construction of the Alyeska pipeline project was largely restrictive; hence, punitive from the standpoint of weld defect repair economics. The real paradox of the Alyeska pipeline case history was, of course, that in spite of the finding approved by NBS, that the discontinuities were innocuous and, despite the DOT waiver, all the discontinuities in question were repaired at a total cost of over $50 million.

III. CONCLUSION

Fitness-for-purpose philosophy is considerably more rational than the present workmanship-based weld acceptance standards. Fracture mechanics principles are a proven and useful tool in assessing the significance of weld defects. Although certain aspects of fracture mechanics are still under refinement, the state of the art is sufficiently developed to begin to formulate specific weld acceptance criteria with respect to the various types of weld discontinuities: notably, slag inclusions and porosity.

Increasing sophistication in inspection techniques makes the development of rational weld acceptance standards all the more important. Compatible with a new weld acceptance criteria, there appears to be an optimum level of weld inspection beyond which the benefits are no longer cost effective.

Existing standards are overconservative and do not address the role of residual stress, “size effect”, interaction effect, discontinuity location and shape differences. Fitness-for-purpose philosophy should not be construed to mean a decrease in weldment quality, rather an increase via outlining the conditions of eliminating unnecessary weld repairs. Weld repair is neither synonymous with an automatic improvement in weldment quality nor an ipso facto elimination of weld discontinuities.

The world literature shows a good agreement in that porosity and slag inclusions are regarded to be least harmful of all weld discontinuities. Ranking of weld discontinuities in descending order of importance is as follows:

1. Cracks and crack-like defects.
2. Geometric discontinuities.
3. LOF/LOP.
4. Slag inclusions.
5. Porosity.

The predominant failure mcde in commercial vessels is fatigue. The incidence of occurrence of brittle fracture is reported to be very few. Therefore, the most important fracture mechanics principle pertinent to merchant ships is the Paris formula:

$$\frac{da}{dN} = C(\Delta K)^{m}$$

Information on corrosion fatigue of ship steel weldments and role of discontinuities in both low- and high-cycle fatigue is sparse. Additional research in these areas is in order. Due to the empirical nature of the treatment of fatigue, safety factors are required to take care of uncertainties in determining the exact magnitude of (a) stresses, (b) discontinuities, *and* (c) heterogeneities in shipbuilding steels and the welds, which influence the fracture toughness.

LEFM has limited usefulness since brittle fracture seldom occurs in commercial ship hulls according to the literature.

Structural design details and joint misalignment constitute the principal causes of ship failures. Weld discontinuities are reported to rank extremely low in causing failures in seagoing commercial ships.

The majority of weld repair activity in U. S. shipyards involves removal of slag inclusions and porosity. An estimated *savings* realized from minimizing weld repair of innocuous weld discontinuities could range from $300,000 to well in excess of $1 million per ship hull.

The “Quality Bands" approach to establishing more rational standards for slag and porosity seems to have a broad support in the international literature.

The new weld acceptance standards should be verified by testing large-scale, full-thickness weldments containing slag inclusions and/or porosity. This experimental program ought to be defined in detail by a Task Force group of experts representing shipyards, classification societies, owner/operators and design offices.

From a fatigue and fracture control point of view of an ocean-going merchant ship the analysis of available data suggests that first priority be given to improving design details and decreasing joint misalignment. Since ship failures are induced by a host of causes, the implementation of a “Quality Control Systems Loop” founded on good feedback and total participation proposes to be most essential and beneficial to the overall improvement in the present state of the American shipbuilding industry.

A Center should be established for seining the American shipbuilding community.

IV. RECOMMENDATIONS

The results of this study suggest, in four specific areas of major interest, the following recommendations.

1. Ad Hoc Task Group

One school of thought of failure analysis advocates the *use* of large scale tests for assessing fatigue failure modes (25, 72-73, 90, 120). They believe that such test(s) are less tenuous and more practical than the intricacies of fracture mechanics principles involved in threading together the interacting effects of crack blunting, strain hardening, crack closure, residual stresses, exhaustion of ductility, the presence of multiple defects of one or more species, micro-structural heterogeneities, inaccuracies in load characterization, and all the possible “second order effects”, necessary to permit a precise forecasting of the in-service behavior of huge welded structures such as ships. The difficulties in modelling all these second order effects in what may constitute a series of mathematical formulations have led to-a scatter in fatigue life results (73).

The suggestions to bring about changes in current standards in general, noted in the world literature, have assumed many forms. Bergemann (121) states that “full reliance on conventional criteria sometimes leads to absolutely wrong conclusions”. The basis of his recommendations is the use of fracture mechanics. O‘Connor proposed that revisions of existing codes could be formulated in accordance with welding process used: "separate acceptance standards for full- and semi-automatic processes” (122). Views on quality control of shipbuilding welds put forth by Dr. Leide and his colleagues (123) are that ship structures might be classified into four groups. The character and size of tolerable defects in a particular ship component may not be identical. An interesting observation voiced by Wyatt (124) is “common sense, forethought and discipline have proved at least as important as basic science and engineering technology”. Howden (125) “predicts that defects acceptable by present day standards will cause problems in the future as the strength level of pipe steel is increased”.

Another proposal includes classification of welds into three quality grades on the basis of fatigue or brittle fracture conditions, type and severity of defects present, statically loaded structures and lightly loaded welds (126). Whether the load acting upon a particular weld defect present in a weld is parallel with or normal to the joint is important in terms of weld defect acceptance criteria. Having recognized this, less stringent standards may suffice (127). Karsai, et al (128) concluded from the model studies conducted on pipeline welds that current Hungarian standards were overconservative, “excessive”. A timely reassessment of relevant weld acceptance standards is needed (1). Reasons given by Professor Lundin are that current codes are for the most part too restrictive in few cases unconservative and sufficient state of the art knowledge now exists on the effects of weld discontinuities on service performance of the weldments.

schutz and others feel (25, 129) that an approach better suited to predict fatigue life than fracture mechanics would be to use “realistic tests with real structures or components. If this is not possible, use models or specimens”, as would be the case for commercial ships, offshore structures.

To begin with, the test method must be standardized to be able to correlate data obtained under different sets of test conditions. The scoping and scaling of fatigue tests are rightfully presumed to fall in the realm of responsibilities of a Task Force Group of experts.

TFG may consist of representatives of shipbuilders, code making bodies, owner/operators, Navy, U. S. Coast Guard and the Maritime Administration to address this problem. They should examine the degree to which existing weld acceptance standards with respect to specific weld discontinuities ought to be liberalized based upon a series of well conceived fatigue tests conducted under worst-case conditions of commercial ship environments (120). The Ad Hoc Group might consider for large scale fatigue testing two or three basic welding processes of SMA, SA, and flux-cored arc, preferably for specific and most important ship components. As test parameters, effects of sea water environment, different load histories, various amounts of slag, porosity, lack of fusion, undercut, crack sizes, and crack locations should be assessed. To shorten the evaluation process, only variable amplitude load histories, different frequencies of stress cycles involving various mean stress levels should be investigated. It might be pointed out that frequency of loading is reported to be important only in the presence of a corrosive environment such as sea water (22, 71, 129-131). Assume 20 or 30 years as the life of a ship. So, the index of life or the number of cycles of fatigue should be estimated on that basis. Each specific test should be repeated enough times to establish a high level of confidence. After that, set up charts for weld defect standards on the basis of load levels and quality bands, easily useable by the practicing inspectors in the shipyard (see examples in Appendix III).

It is worth remembering that over the years the quality of steels and filler metals have undergone much improvement. As a result, weldments of today have much greater tolerance for discontinuities than those of the Liberty ships era. By and large, specifications have not reflected this change. Rules still rely heavily on old traditions, hearsay and fear (62). Suffice it to say that existing standards ought to be modified to take notice of these improvements in both the quality of materials used and our contemporary understanding of weldment behavior. When all is accomplished, ship quality shall be better for it.

The practical translation of the meaning of fracture mechanics on fatigue could take the form of "allowable defect size curve" determined by the Task Group (7, 60). The National Bureau of Standards' approach (132) to these "curves" "will be based on:

1. applied stress levels
2. fracture toughness levels
3. defect size

All defects will be assumed as surface cracks. Such a scenario appears too conservative for commerical ships because most of the discontinuities found in welds are buried slag inclusions and porosity.

For purposes of fracture mechanics calculations, the shipbuilding steels may be grouped according to:

1. high fracture toughness
2. intermediate fracture toughness
3. low fracture toughness

The Task Force concept is not new, nor is it ever permanent by definition. Pooling together a group of leading experts under an umbrella of one kind or another has often been used to implement certain special tasks. The Pressure Vessel Research Committee in its 1979-80 Annual Report mentions that the Subcommittee on Elevated Temperature Design formed a Task Group on “international benchmark problems”. One of the Group’s objectives involves the “development of acceptance criteria for weld defects in elevated temperature service to assist the ASME Boiler and Pressure Vessel Code” in this endeavor (89). This is a modest indication that the efforts of many years of research and test expended internationally on the significance of weld defects is beginning to pay off in bringing about changes needed in existing codes. Code-making bodies for shipbuilding should follow suit.

2. <u>Information Center</u>

Improvements in product performance come from comprehensive assessment of technologies and data available. The confidence level of the conclusions deduced depend to a very large extent upon the size of the data bank and the degree of accuracy with which it has been acquired. Information gathering ought to be systematic, continuous and all-encompassing. Studies such as the one conducted by C. R. Jordan and C. S. Cochran of Newport News Shipbuilding are extremely beneficial in providing “feed-back” data to the engineer and designer who develops a design and never receives the performance data that is needed for future improvements, growth and increased confidence (26].

Another important observation they point up in their report is that "orderly and systematic study of structural details on ships in service can make a significant contribution to design and repair knowledge that should result in an improvement in design and fabrication practices and increase the number of sound details in present and future ships”. In their Part II continuation report, a survey was conducted on the midship section of thirty-six ships: twelve bulk carriers, twelve container ships and twelve general cargo ships (27). This survey reconfirmed many of the failure trends established in the first fifty ship survey. However, distinctive service performances were identified in the second survey. The data from the two surveys were summed up to make all this information readily accessible to interested personnel. The highlight of the overall conclusion is that failures are attributed to “one or a combination of five categories: design, fabrication, welding, maintenance and operation” (27).

A task of this magnitude is certainly too large and expensive to be supported solely by any individual shipyard. Even if a single, enterprising yard would attempt to set out on a project like this, it would take too long to compile an adequate data bank. As Messrs. Jordan and Cochran put it, “Projects of this type should be a continuing effort. As more ships are surveyed, there is less need for estimated data as used in the first survey. Eventually, a substantial data base is formed from which meaningful statistical analyses can be conducted to provide useful information to ship owners as well as design offices." A typical example to a ship owner/operator and a design office might be a better assessment of ship maintenance economics and selection of improved detail configuration suitable for a specific design situation, respectively. A valuable feedback to a shipbuilder might, on the other hand, be a well-defined welding parameter or defect having contributed to a specific failure mode. This knowledge should pre-empt the same problem from re-occurring in the future in identical situations.

The Center may wish to consider the statistical approach to determining the relationship of type, size, and amount of weld defects to causing frequency of specific failure modes in specific welds and weldments. A correlation between the original inspection data and the service performance of the inspected welds irrespective of the presence or absence of discontinuities would be most fruitful. Today this sort of a correlation is not done. We do not know how the inspected joints fair in service. On this, there is no feedback to the QA or QC Department. In the present system of quality assurance, the only time information is supplied from the field is if there is a failure. The present system of information flow does hot as a rule identify whether or not the data represents originally inspected or noninspected weldment sites. A system is good if it lends itself to clear-cut correlations thereby ultimately leading to better characterization of:

1. Usefulness of inspection methodologies.
2. Weld defect acceptance standards.
3. Direction in which to proceed to augment the level of confidence in the total system and attainment of optimum weld acceptance standards.

Synthesis of data and information yields definitive cause-and-effect relationship, pinpointed areas of improvement, reduced weld repair costs and improved product quality. such an approach minimizes guessing.

Establishment of a Center for serving the American Shipbuilding Industry could turn out to be a noble idea. The Center might best be viewed as a mechanism for disseminating information of what its voluntary membership would deem economically and technologically productive; e.g., periodic reassessments of weld defect and design standards, information storage and retrieval, training, etc. (133).

While there are various committees entrusted to carry out certain responsibilities, there is now no satisfactory vehicle in the U. S. shipbuilding industry to coordinate, monitor, analyze, disseminate statistical data, information and enhanced knowledge not only in the art of welding but in other relevant engineering disciplines on a concerted, ongoing basis and in sufficient depth. It is in the interest of everyone that we create a good line of communication among shipbuilders, materials producers, classification societies, design firms, and owner/operators with respect to our best understanding on the *real* role of weld discontinuities and growing experience. In such a climate, one does not become an inflexible guardian of the status quo.

The economic consequences of occasional defects or local structural problems induce shipyards to impose high standards of quality often times independent of relevant classification societies (3). This is a commendable act. However, it tends to mean that one needs first a disaster before appropriate actions are taken.

3. <u>Quality Control Systems Loop</u>

In a large and complex industrial environment a great deal of the inspection effort goes into determining the cause of sudden loss of quality or of diminishing workmanship. The Quality Control Systems Loop (QCSL) advocated can be an inexpensive answer to that problem.

Important elements of this quality control systems loop would be:

a. Quality planning by quality control department together with appropriate engineering and production personnel.

b. Appraisal of the plan by process control engineering persons to check the compliance of the plan with relevant standards.

c. Feedback of data and analysis thereof by process control engineering, manufacturing or production departments in order to determine the need for possible changes, new planning, corrective actions.

d. Continuous audit of QC plan to ensure satisfactory workmanship, conformance.

e. Upkeep of training and teaching people about the vital role of an all-encompassing quality control systems approach, which serves everyone's interest.

The reader is referred to Appendix I showing the schematic of the Quality Control Systems Loop. The implementation of such a system requires time. Its effectiveness will be a function of the degree of participation and the nature of the attitudes of the participants. If QCSL is properly formulated and implemented by the total work force of *a given* shipyard it should unquestionably be less costly and far more efficacious of a tool to achieve the desired objective than that through the hiring of more inspectors or more NDT methods. After all, the affordable cost of QC inspectors and NDT methodologies is finite. It is more so in times of austerity in a given industry than when that industry enjoys an economic prosperity. Certainly, the shipbuilding industry has of late been in the former economic state. Let us face it; ultimately, quality control and its guarantee are in the hands of the people who build the product and not in mere policing the rules of the game, or writing standards. This philosophy does not intend to ignore the proper share of "formal inspection" and the application of NDT methods and instrumentations. The QCSL is predicated upon setting up a proper balance of all the elements making up the total system. Analogous to the proposed QCSL, the U.S. Navy and Air Force started to use sometime ago the so-called “Fracture and Fatigue Control Plan” (134-135) or “Flaw Tolerance Control Plan” (136-137). The Plan has a Fracture and Fatigue Control Board headed by the Chairman who reports directly to the President [e.g., of Lockheed Aircraft Company (134)]. Reporting to the Fr.F.C.B. Chairman are the following functions along the QC or QA framework: testing, material analysis, welding, manufacturing, procedures, drawings, qualifications and certification of personnel, reliability demonstration, NDT parts plan, materials and parts classifications, facilities and equipment conditions, maintenance, education and training of personnel.

Factors affecting acceptance criteria and quality include not only considerations for standards, specific agreements, notion of fitness-for-purpose, but also for type and scale of accepted practice and continued education of welders, supervisors, inspectors, welding engineers, designers, managers and others (138).

It is not so important whether the systems approach is centralized or decentralized as that all the ingredients of the total plan are integrated to ensure the success of the system. As of 1975, Japan used the decentralized approach, while Europe tended toward the use of the centralized system (a notable exception was Sweden). Lately, participation of the workers has begun to increase along the lines of the Japanese system (104).

Engineering materials, components and structures are not perfect. They contain numerous material flaws, manufacturing defects and design discontinuities. In view of such well. established facts, it is inappropriate to presume that a structure will fail as a consequence of diverse discontinuities inadvertently introduced. More properly the fatigue and fracture control of built structures should be approached by means of statistics. In other words, how many, how large discontinuities may be present and whereabouts in the structure do they lie. Are these defects located in a highly stressed or in a non-load bearing component of the engineered structure? Is the discontinuity benign or detrimental to the performance of the weldment under the loading condition and service environment anticipated? Considerations should also be given to the propensity of the component for premature failure which could arise from a whole host of contributory factors. Unfortunately, information on the distribution of discontinuities is rare (5).

Statistical data gathering is not easy, but is a very useful task. Since the parameters used to carry out fracture mechanics calculations are random variables - if for no other reason than the inherent heterogeneity in the microstructure of materials. The probabilistic fracture mechanics approach would be helpful to establish a range for the respective variables: hence, a greater reliability of predicting the ultimate behavior of-the structure.

Keeping in-process records that are comprehensive enough in an engineering and statistical sense can take on a rather emotional aspect. However, documentation of comprehensive data is a must if we are to eliminate repetitive errors. Good record keeping is a foundation of evaluation: identification of problems, detection, correction, prevention of defects, reoccurrence of manufacturing faults, dimensional controls, misalignments, fit-up problems, structural design details, etc. Along with others (39, 101, 139-140), Volchenko (141) advocates the importance of "statistical control of the technological process". Konkoly (142) did a quantitative evaluation of the effect of weld defects upon the susceptibility of steels to brittle fracture. So, the importance of data compilation has been well recognized in the international literature. The probabilistic fracture mechanics approach to shipbuilding weld standards is quite real due to more uncertainties associated with seagoing vessels than land-based structures.

An extremely significant benefit that springs from QCSL is an early awareness of the occurrence of weld defects and other discontinuities in the process cycle of material and product flow. The present "formal inspection system" lends itself to discontinuity accumulation giving rise to excessive repair costs. QCSL is like an early warning system for discontinuity acceptance standards observed by all the participants during fabrication as well as in service. It leads to elimination of repetitive defects. QCSL is, by its very nature, an evolutionary procedure. Nevertheless, it will eventually be self-policing and self-regulatory without resorting to additional inspectors to impel improvements in the entire system.

The practice of quality control must not be viewed by shipyard management as an isolated entity or as a privilege of a designated few, but a part and parcel of the total system. Considerations given to a part of the system invariably does bear upon other segments of the very same system. A good illustration of this point would be to single out the strong relationship between accuracy - better known as “fit up” in the shipbuilding industry - and quality control. Accuracy has to do with technology; inter alia, jigs, tools, modern up-to-date equipment to attain a good fit-up. Quality control on the other hand means the achievement of an acceptable workmanship in accordance with a certain set of requirements. Accuracy in the prefabircation stage is needed in order to insure a satisfactory quality level. Fit-up will influence weld quality (104). In the absence-of available accuracy, a satisfactory quality control level cannot be achieved without severe manufacturing cost penalties.

It is necessary to compile quality control data so as to be able to establish tolerance limits. The analysis of the data will in turn permit the defining of quality trends or ranking of problem areas. Once these trends or problem areas are determined it then becomes considerably easier to delineate the course(s) of corrective action(s). Phillip (104) makes the suggestion that the quality of workmanship and dimensional accuracy be checked right from the start of building a ship, at prespecified *stages* during fabrication and erection. Competition among shipyards of the world does not allow room for inferior quality (104). The dictates of economics and competition engenders what may be called "The System Approach" to quality control rooted in a continuous feedback.

The Japanese approach to quality control is, "Produce better quality products by performing proper work according to the Standards. Eliminate defects before they occur" (39). According to Kobayashi, the QC system is set up on the basis of:

a. Statistical methods
b. Self-quality checks by the workers

The latter helps promote morale among the workers, for they feel they are an integral part of the total system. A greater awareness of the importance of quality workmanship on the part of the work force eventually leads not to the hiring of more inspectors, rather the reduction in the cost of inspection and amount of repair. A natural consequence of total participation is an enhancement of the level of quality of the entire system without an accompanying rise in the cost of quality control. Undoubtedly, this is a developmental process. It requires education or even re-education is some cases.

The Japanese seem to pay more attention than their American peers not only to the final inspection and to the workers' morale in the maintenance of good quality, but to the in-process quality control as well. In Japan the results of inspection are used as illustrations in the continued education of welders.

Despite voluminous publications all throughout the world written over the decades by an awesomely impressive array of scientists, engineers, technologists and others, the acceptance of fracture mechanics has shown a very slow progress. why?-- It is *in* the aggregate interest of the academic, research, industrial and code making communities to unravel the answer. Perhaps a world conference held for this purpose and in which universities, research institutions, industry, classification societies and users of welded products would be drawn together in sufficient numbers might turn out to be a decisive forum and a cornerstone event. We just might find out in such a gathering that too much information has been left laying scattered in too many of the world's publications: hence, its desired effects fragmented and full impressions inadequately realized by all concerned. No doubt, a few arguments and travails would be generated, but it is hoped that from them would come a better understanding for designers, metallurgists, welding engineers, inspectors and surveyors.

4. <u>Proposed Weld Acceptance Standards</u>

The statistical analysis of available quality control data and information showed that the preponderance of weld repair activity in the commercial sector of the U.S. shipbuilding industry involved slag inclusions and porosity. It is, therefore, proposed that first priority be given to the establishment of new, improved weld acceptance standards with regard to said weld discontinuities. Most of the savings - solely in terms of weld discontinuities - would come from minimizing unnecessary weld repair due to slag inclusions and porosity. Moreover, said weld discontinuities constitute the least harmful of all weld defects recognized by the world literature.

In terms of relaxation of existing weld acceptance standards for slag inclusions and porosity, the exemplary format of proposed standards - shown in Appendix III - may be used as a point of departure for reassessment by a commissioned Ad Hoc Task Group. In fact, each specific point in all of the recommendations mentioned is intended merely as a suggestion. It is up to the judgements and best discretions of the Task Force to deal with specific engineering details, priorities and cost-, duration-, and quantity-of tests.

ACKNOWLEDGEMENT

Sun Ship, Inc. wishes to express its appreciation to Bath Iron Works for awarding this subcontract and the U. S. Maritime Administration for sponsorship. The author is pleased *to* recognize the helpful discussions and comments made by Dr. John D. Harrison, The Welding Institute, Cambridge, UK, and Professor Carl D. Lundin, University of Tennessee, Knoxville, Tennessee, USA, for reviewing the manuscript. Special “thanks” are extended to the many experts in several U. S. shipyards and the American Bureau of Shipping for the supply of quality control data and the forthright exchange of views.

I am ”particularly grateful to two of my colleagues at Sun; Dr. Richard T. Bicicchi for guidance and encouragement throughout this study and Mr. Thomas P. Krehnbrink for valuable comments on the manuscript. Mrs. Denise Cacciatore deserves recognition for her diligence in typing the report.

REFERENCES

1. Lundin, C. D., "The Significance of Weld Discontinuities - A Review of Current Literature, " WRC Bulletin #222, December 1976.

2. Basar, N. S., et *al,* "Survey of Structural Tolerances in the United States Commercial Shipbuilding Industry, " M. Rosenblatt and Son, Inc. , SSC-273, 1978.

3. Santini, W., "Quality Standards and Quality Control in Shipbuilding: A Joint Task of Shipyard and Classification Society," Paper 29, International Conference, London, November 18-20, 1975, Vol. 1, TWI, Cambridge, 1976.

4. Harrison, J. D., et al, "The Acceptability of Weld Defects," The Royal Institution of Naval Architects, Spring Meetings, 1974.

5. Harrison, J. D., "Application of Fracture Mechanics in the Prevention of Service Failures," The 3rd National Symposium of the Japan Welding Society, September 1978, Tokyo.

6. Gurney, T. R., "Theoretical Analysis of the Influence of Toe Defects on the Fatigue Strength of Fillet Welded Joints," TWI Research Report, 32/1977/E, March 1977.

7. WRC Progress Reports, Vol. XXXII, No. 11 (Nov. 1977), NO. 12 (Dec. 1977), Vol. XXXIII, No. 4 (April 1978), Vol. XXXIII No. 5 (May 1978), No. 7 (July 1978), NO. 10 (Oct. 1978).

8. Screm, G., et al, "The Effect of Weld Defects in Reducing the Fatigue Strength of Welded Joints," Alluminio, Vol. 44, No. 3, March 1975.

9. Bailey, N. and Miss "David, M.L.E., "Fluxes for submerged Arc Welding Ferritic Steels - A Literature Survey," Part 2: Weld Properties and Weld Defects, TWI Research Report, 10/1976/M, May 1976.

10. Boulton, C. F., "The Influence of Surface Porosity on the Fatigue Strength of Butt Welded Joints", TWI Research Bulletin, Vol. 18, No. 2, February 1977, pp. 41-45.

11. Harrison/ J. D., et al, "A Re-analysis of Fatigue Data for Butt Welded Specimens Containing Slag Inclusions," TWI Research Report #37/1977/E, April 1977.

12. British Standards Institution, "Draft PD for Guidance on Some Methods for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints," London, June 1978.

13. Harrison, J. D., “Basis for a Proposed Acceptance Standard for Weld Defects. Part II: Slag Inclusions, ” Metal Construction and British Welding Journal, Vol. 4, No. 7, July 1972.

14. Boulton, C. F., “Acceptance Levels of Weld Defects for Fatigue Service,” Welding Research Supplement, Welding Journal, January, 1977.

15. Nichols, R. W., “Interrelationships between Mechanical Properties and the Significance of Defects,” Proceedings, Second International Conference on Pressure Vessel Technology, San Antonio, Texas, October 1-4, 1973, ASME, 1974.

16. Harrison, J. D., “The Effect of Herringbone Porosity on the Fatigue Strength of Butt Welds,” TWI Research Bulletin, Volume 18, No. 7, July 1977, pp. 175-178.

17. Thielsch, H., “The Sense and Nonsense of Weld Defects,” Monticello Books, Chicago Ill., 1967.

18. Soete, W., et al, “Influence of Weld Defects on High-Fatigue Behavior,” Pressure Vessel Technology II - Materials and Fabrication, First International Conference, sponsored by ASME and Koninklijk Instituut van Ingenieurs, September 29-October 2, 1979, Delft, The Netherlands, New York, 1969.

19. Burdekin, F. M. et al, “The Effect of Weld Defects with Special Reference to BWRA Research,” Welding Research Abroad, Vol. 14, No. 7, August/September 1968.

20• Harrison, J. D., “Basis for a Proposed Acceptance Standard for Weld Defects. Part 1: Porosity," Hetal Construction and British Welding Journal, Vol. 4, No. 3, March *1972,*

21. Ishii, Y., et al, “An Analysis of Intermediate Cycle Fatigue of Defective Welded Joints,” Transactions of the Japan Welding Society, Vol. 3, No. 2, September 1972.

22. Nibbering, J. J. W., et al, “Some Considerations for Fracture-Safe Design of Maritime Structures,” Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

23. Knight, J. W., “Corrosion Fatigue of Steel Structures in Sea Water,” TWI Research Bulletin, Vol. 17, No. 4, April 1976, pp. 91-94.

24. Irving, R. R., “Will Code Bodies Accept Fitness for Purpose?” Iron Age, September 11, 1978.

25. Schutz, w., "The Prediction of Fatigue Life in the Crack Initiation and Propagation Stages - A State of the Art Survey, " Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

26. Jordan, C. R., et al, "In-Service Performance of Structural Details," Newport News Shipbuilding, Contract #NOO024-76-C-4362, U. S. Coast Guard, Washington, D.C., 1978.

27. Jordan, C. R., et al, "Structural Details Failure Survey, Part II," Newport News Shipbuilding, Contract No. DOT-CG-75172-4, U. S. Coast Guard, Washington, May 1979.

28. Harrison, J. D., "The Application of Fracture Mechanics to Welded Structures," Seminar on Use of Fracture Mechanics to Assess Weldment Reliability, Washington University, St. Louis, Missouri, October 26, 1978.

29. "Use of Fracture Mechanics to Assess Weldment Reliability." Seminar Held at Washington University, St. Louis, Missouri, October 26, 1978, by The Center for Fracture Mechanics and The Welding Institute. Lecturers: Drs. A. A. Wells, J. D. Harrison, Professors P. C. Paris, C. E. Turner, and G. R. Irwin.

30. Dolby, R. E., "HAZ Toughness of Structural and Pressure Vessel Steels - Improvement and Prediction, " Welding Journal, August 1979.

31. Kikuta, Y., et al, "A Study on Microstructure and Precipitate in HAZ and Reheated Zone of Weld Metal of Structural Steel," Criteria for Preventing Service Failure in Welded Structures, Proceedings, 3rd International Symposium of the Japan Welding Society, Tokyo, September 26-28, 1978.

32. Bernard, G., "A Viewpoint on the Weldability of Carbon-Manganese and Microalloyed Structural Steels," Microalloying 75 Proceedings, Union Carbide Corp., 1977.

33. Jesseman, R. J., et al, "Influence of Some Steelmaking Variables on Ship Plate Weldment Toughness, " Welding Journal, August 1979.

34. Once, H., et al, "Japanese LPG Tanker Constructed Using a New Welding Process and Improved Al-Killed Steels, " Metal Construction 11 (1), 1979.

35. Hannerz, N. E., "Effect of Stress Relieving Heat Treatment on the Toughness Properties of Simulated HAZ's in V-Alloyed Steels, " Schweissen and Schneiden, 28 (10), 1976.

36. *Once, Y.,* et al, "Improvement in Steel Properties by Sulphide Shape Control, " Trends in Steels and Consumables for Welding, International Conference by the Welding Institute, London, November, 1978.

37. Pisarski, H. G., "Influence of Thickness on Critical Crack Opening Displacement (COD) and J Values," TWI Research Report, 90/1979, May 1979.

38. Winn, W. H., "Quality Assurance in Welded Ship Structures Designed on a Limited Budget, " Paper 27, International Conference, London, November 18-20, 1975, Vol. I, TWI, Cambridge, 1976.

39. Kobayashi, K., "Quality Control in Shipbuilding, " Paper 28, International Conference, London, November *19-20, 1975,* Vol. I, TWI, Cambridge, 1976.

40. Walter, J. C., et al, "New Trends in the Application and Evaluation of Non-Destructive Testing, " International Conference on Quality Control and Nondestructive Testing in Welding, London, November 19-21, 1974, The Welding Institute, 1974.

41. "*Welding* in the World, " Vol. 15, No. 9/10, 1977.

42. *WRC* Progress Reports, Vol. XXXIV, No. 10, pp. 40-41, October, 1979.

43. The Welding Institute, "Significance of Weld Defects, " Weldasearch System 2 and Literature Abstracts from 1967-1978.

44. Hertzberg, R. W., "Deformation and Fracture Mechanics of Engineering Materials, " John Wiley and Sons, New York, 1976.

45. Reed, R. P., et al, "A Fracture Mechanics Evaluation of Flaws in Pipeline Girth Welds, " WRC Bulletin #245, January, 1979.

46. Dawes, M. G., "Contemporary Measurements of Weld Metal Fracture Toughness, " Welding Journal, December, 1976.

47. Davidson, D. L., et al, "Crack Tip Plasticity Associated with Corrosion Assisted Fatigue," Southwest Research Institute #02-4268 for Office of Naval Research NRO-36-109/2-25-76 (471)., May 31, 1978.

48. WRC Long-Range Planning Committee, Department of Commerce Technology Program, WRC Progress Reports Vol. XXXIV, No. 1, January 1979.

49. Trans-Alaska Crude Oil Pipeline, Petition for Waiver of Girth. Weld Defects at the Valdez Terminal, Docket No. 77-9W, Federal Register, Vol. 44, No. 28, Thursday, February 8, 1979.

50. Dover, W. D., et al, "A Fracture Mechanics Analysis of the Fatigue Failure of T-Joints Subject to Random Loading, " Integrity of Offshore Structure, International Symposium, April 6-7, 1978, Glasgow, Scotland.

51. McEvily, Jr. , A. J., "The Fracture Mechanics Approach to Fatigue, " Significance of Defects *in* Welded Structures, Proceedings of the Japan-U. S. Seminar, 1973, Tokyo, University of Tokyo Press, 1974.

52. Irwin, G. R., et al, "Summary of Fracture Mechanics Concepts, " *Seminar* on Use of Fracture Mechanics to Assess Weldment Reliability, Washington University, St. Louis, Missouri, October 26, 1978.

53. Wells, A. A., "Background to the Fracture Mechanics Approach to Fracture Control of Weldments, " Seminar on Use of Fracture Mechanics to Assess Weldment Reliability, Washington University, St. Louis, Missouri, October 26, 1978,

54. Turner, C. E., "Fracture Toughness: Material Behavior and Test Procedures, " Seminar on Use of Fracture Mechanics to Assess Weldment Reliability, Washington University, St. Louis, Missouri, October 26, 1978.

55. Paris, P. C., "Elastic-Plastic Fracture Mechanics Fundamentals," Seminar on Use of Fracture Mechanics to Assess Weldment Reliability, Washington University, St. Louis, Missouri, October 26, 1978.

56. Dawes, M. G., "Elastic Plastic Fracture Toughness Based on The COD and J Contour Integral Concepts, " TWI Research Report #54/1978/E, January 1978.

57. Harrison, J. D., et al, "The COD Approach and Its Application to Welded Structures, " TWI Research Report #55/1978/E, January 1978.

58. Kobayashi, A. A., "Experimental Techniques in Fracture Mechanics, " No. 1, 1973, No. 2, 1975, SESA.

59. Paris, P. C., "Fracture Mechanics in the Elastic-Plastic Regime, " ASTM Publication 631, 1977.

60. National Bureau of Standards, "Consideration of Fracture Mechanics Analysis and Defect Dimension Measurement Assessment for The Trans-Alaska Oil Pipeline Girth Welds, Vols. 1 and 2, PB-260400, PB-260401, Washington, D. C., October *1976.*

61. The Oil and Gas Journal, a series of articles published in 1976 on Alyeska pipeline weld flaws, inspections, repairs, and waver requests.

62. Harrison, J. D., "The Welding Institute Studies the Significance of Alyeska Pipeline Defects," TWI Research Bulletin, Vol. 18, No. 4, April 1977, pp. 93-95.

63. Bosworth, T. J., "The Application of Fracture Mechanics to Weld Quality Control - A Concept," The Boeing Company, Paper presented at AWS Annual Meeting, Cleveland, Ohio, April 20-24, 1970.

64. Gudas, J. P., et al, "Elastic-Plastic Fracture Toughness (J_{Ic}) of High Strength Steels and Titanium Alloys," David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland, June 1978, AD-A056 091.

65. Gurney, T. R., "Theoretical Analysis of the Influence of Attachment Size on the Fatigue Strength of Transverse Non-Load-Carrying Fillet Welds," TWI Research Report #91/1979, May 1979.

66. Wilkowski, G. M., et *al,* "Review of Fracture Mechanics Approaches to Defining Critical Size Girth Weld Disconti- nuities," WRC Bulletin #239, ISSN 0043-2326, July 1978.

67. Draft British Standard - "Methods for Crack Opening Displacement (COD) Testing," Private Circulation, Sub- Committee ISE/NFE/4/4, February 1978.

68. "Dynamic Fracture Toughness," International Conference by The Welding Institute and The American Society for Metals, London, July 5-7, 1976.

69. Thaulow, C., "Comparison Between COD and Charpy Results on C-Mn Steel Weld Metal," Metal Construction, The Journal of the Welding Institute, December 1978.

70. Irving, R. R., "New Energy Needs Test Welding's Mettle," Iron Age, December 12, 1977.

71. Francis, P. H., et al, "Subcritical Crack Growth and Ship Structural Design," Marine Technology, Vol. 13, No. 2, April 1976.

72. Gurney, T. R., Discussion of Professor Nibbering's paper given at International Symposium on "Integrity of Offshore Structures, April 6-7, 1978, Glasgow, Scotland.

73. Turner, C. E., Ibid.

74. "Criteria for Preventing Semite Failure in Welded Structures," 3rd International Symposium of the Japan Welding Society, September 26-28, 1978, Tokyo.

75. Perrone, N., et al, "Fracture Mechanics," 10th Symposium on Naval Structural Mechanics, Washington, 1978, The University Press of Virginia, 1978.

76. McHenry, H. I, et al, "Fracture Mechanics Analysis of Pipeline Girthwelds," Symposium on Elastic-Plastic Fracture, Atlanta, Georgia, November 16-18, 1977.

77. Berger, H., et al, "Consideration of Fracture Mechanics Analysis and Defect Dimension Measurement Assessment for the Trans-Alaska Oil Pipeline Girth Welds," NBSIR-76-1154-Volume 1, DOT/MTB/OPSO-76--02, Washington, D. C.

78. Weck, R., "A Rational Approach to Standards for Welded Constructions," British Welding Journal, November 1966.

79. Wells, A. A., "Brittle Fracture in Welded Structures: Contemporary View," Welding Metal Fabrication, 29(3) 89-94, March 1961.

80. Nibbering, J. J. W., "Fracture Mechanics and Ships," Proceedings of an International Conference, Delft, Netherlands, June 24-28, 1974.

81. Gurney, T. R., et al, "A Revised Analysis of the Influence of Toe Defects on the Fatigue Strength of Transverse Non-Load-Carrying Fillet Welds," TWI Research Report, 62/1978/E, April 1978.

82. Pellini, W. S., "Design Options for Selection of Fracture Control Procedures in the Modernization of Codes, Rules and Standards," and "Analytical Design Procedures for Metals of Elastic-Plastic and Plastic Fracture Properties," WRC Bulletin #186, August 1973.

83. Rolfe, S. T., et al, "Fracture and Fatigue Control in Structures," (Application of Fracture Mechanics), Prentice-Hall, Inc., 1977.

84. Rolfe, S. T., et al, "Fracture Control Guidelines for Welded Ship Hulls," Project SR-202, "Fracture Criteria," Department of the Navy, Naval Ship Engineering Center, Contract No. NOO024-72-C--5316, Washington, D. C., 1974.

85. May, R. A., et al, "Effective Utilization of High-Yield Strength Steels in Fatigue," WRC Bulletin #243, November 1978.

86. Sanders, Jr., W. W., et al, "Fatigue Behavior of 5000 Series Aluminum Alloy Weldments in Marine Environment," WRC Bulletin #242, October 1978.

87. Burk, J. D., et al, "Effects of Lack-of-Penetration and Lack-of-Fusion on the Fatigue Properties of 5083 Aluminum Alloy Welds," WRC Bulletin #234, January 1978.

88. Dorn, L. et al, "The Influence of Welding Defects on Brittle Fracture Behavior in Arc Welding" DVS Berichte, No. 45, Proceedings, SLV Berlin Jubilee Conference, Occupational safety, Quality control Thermal cutting, Berlin, May 11-13, 1977, published: Dusseldorf, Deutseher Verlagfur Schweisstechnik, 1977.

89. Pressure Vessel Research Committee, 1979-80 Annual Report.

90. Christopher, P. R., "Fatigue and Fracture in Relation to Fabrication of Structures, " Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

91. Miyoshi, S., "Detectable Weld Defects by Current NDT Code, " Seminar on Significance of Defects in Welded Structures, Tokyo, October 15-19, 1973, published by University of Tokyo Press, 1974.

92. Ship Structure Committee, 1977, "A Guide for Interpretation of Nondestructive Tests of Ordinary-Medium- and High Strength Low-A1loy Steel Butt-Joint Weldments in Ship Hull Structures, " SSC-245.

93. "Rules" for Nondestructive Inspection of Hull Welds, " American Bureau of Shipping, 1975.

94. Hennison, J., "Examples of Nondestructive Testing of Very Thick Welds on Pressure Vessels, " Soudage et Techniques Connexes, Vol. 26, No. 11-12, November-December 1972.

95. Kucera, J., "Admissible Defects in Welded Turbine Rotors}" Strojirenstvi, Vol. 22, No. 3, 1972.

96. Frederick, G., et al, "Reflections on the Significance of Defects Observed by Ultrasonic Methods, in the Light of Fracture Mechanics, " Revue de la Soudure/Lastijdschrift, Vol. 28, No. 1, 1972.

97. "Significance of Defects in Welded Structures, " Proceedings of the Japan - U. S. Seminar, 1973, Tokyo, University of Tokyo Press, 1974.

98. Fisher, J. W., et al, "Design, Structural Details and Discontinuities in Steel," Proceedings, ASCE Conference, "Safety and Reliability of Metal Structure, " Pittsburgh, PA, November 2-3, 1972, published by ASCE, 1972.

99. DeSantis, R., et al, "Ultrasonic Control Procedures in Pressure Vessels Fabrication. The Interdependence of Acceptance Standards for Thick Plate and Welds ," Metallurgia Italia, Vol. 69, No. 3, March 1977•

100. Tenge, P., et al, "Acceptance Criteria for Weld Defects and Non-Destructive Inspection Procedures for LNG Tanks in Ships, " Metal Construction, Vol. 7, No. 1, January 1975.

101. Kazinczy, F. de, "Possibilities of Using Non-Destructive Testing to Evaluate Critical Defect Dimensions from the Viewpoint of Fracture Mechanics, " Svetsen, VOl. 33, No. 3, May 1974.

102. Meyer, H. J., "Effects of Defects in Sheet on the Failure of Weld Seams When Strained Normal to the Surface, " Bander-Bleche-Rohre, Vol. 9, December 1968.

103. Young, J. G., "The Evolution of Acceptance Standards for Weld Defects," British Journal of Non-Destructive Testing, Vol. 18, No. 5, September 1976.

104. Phillip, L. D., "An Introduction to Quality Control in Ship Construction," Paper 30, International Conference, London, November 18-20, 1975, Vol. 1, TWI, Cambridge, 1976.

105. Valland, G., et al, "Which Welding Defects Can Be Accepted?, " Sveiseteknikk, Vol. 31, No. 2, May 1976.

106. Lancaster, J. F., "Failures of Boilers and Pressure Vessels: Their Causes and Prevention," International Journal of Pressure Vessels, Piping, 1(2) 48-63.

107. Week, R., "How Dangerous are Weld Defects," Proceedings, 5th International Conference on NDT, Montreal, Canada, May 1967.

108. Ship Structure Committee, 1976, "A Guide for the Non-destructive Testing of Nonbutt Welds in Commercial Ships," Parts I and II, SSC-253, 254.

109. Tenge, P., et al, "Influence of Weld Defects on Low Cycle, High Strain Fatigue Properties of Welds in Offshore Pipe-Lines," Norwegian Maritime Research, No. 3/1977.

110. Collins, R. V., et al, "Field Testing and Repair of Steel Transmission Poles," Welding Journal, May 1978.

111. Pense, A. W., "Recent Experience with Electroslag Welds," Triple Engineering Show, Philadelphia, November 8, 1978.

112. Lauriente, M., "Fracture Problems in the National Transportation System," Fracture Mechanics, Symposium on Naval Structural Mechanics, 10th, Washington, University Press of Virginia, 1978.

113. McEvily, Jr. , A. J., “On the Role of Defects in Crack Initiation in Welded Structures, ” Significance of Defects in Welded Structures, Proceedings of the Japan - U.S. Seminar, 1973, Toyko, University of Tokyo Press, 1974.

114. Baker, M. J., "Safety Approaches for Structures Subject to Stochastic Loads,” Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

115. Kapadia, B. M., “Influence of Residual Stresses on Fatigue Crack Propagation in Electroslag Welds,” Fatigue Testing of Weldments, ASTM Symposium, Toronto, Canada, May 1-6, 1977.

116. Saunders, G. G., et al, “VSR--a current state-of-the-art appraisal,“ International Conference: “Residual Stresses in Welded Construction and their Effects,” London, November 15-17, 1977, The Welding Institute, Cambridge, 1978.

117. Harrison, J. D., “Drop Weight Tests on Standard Specimens and Specimens with Arc Strikes,” The Welding Institute, LD22062/2, July 1976.

118. Gooch, T. G., et al, "Stress Corrosion Tests on Pipeline Weldments: Results of Test Programme,” The Welding Institute, ID22062/6, August 1976.

119. Trans Alaska Crude Oil Pipeline,” Federal Register, Vol. 44, No. 28, 2/8/79.

120. Alia, B., private correspondence, American Bureau of Shipping, February 21, 1979.

121. Bergemann, W., “Weld Defects and Fracture Mechanics,” Schweisstechnik (Berlin), Vol. *24, No. 4,* April 1974.

122. O’Connor, J. H., “An Evaluation of Present and Future Requirements Governing Standards of Acceptability of Girth-Joint Weld Defects in Gas Transmission Pipelines,” International Journal of Pressure Vessels and Piping, Vol. 1, No. 1, January 1973.

123. Leide, N. G., et al, “View on Quality Control on Welding in Shipbuilding,” Zvaranie, Vol. 20, No. 9-11, September-November, 1971.

124. Wyatt, L. M., “Towards Better Welds in Power Plant,” Australian Welding Journal, Vol.*15, No. 7,* September *1971.*

125. Howden, D. G., "A Dimension of Weld Defects and Causes of Failures in Pipelines,”paper given at Annual Congress, Associacao Brasileira de Metais, Porto Alegre, Brazil, July 1974.

126. Vetters, A., "Welded Joints - Defects and NDT," Testing, Instruments and Controls, Vol. 11, No. 7, July 1974.

127. Bornscheuer, F. W., "Criteria for the Dimensioning of Butt Joints in Welded Steel Structures under Predominantly Static Loading," Part 1 and 2, Schweisstechnik (Vienna), Vol. 30, No. 9 and 10, September, October, 1976.

128. Karsai, I., et al, "The Connection Between Weld Metal Toughness and Acceptable Defect-Levels," Proceedings, 7th Conference on Welding, Budapest, June 7-11, 1976, published: H-1428 Budapest, OMKDK-Technoinform 1976.

129. "Integrity of Offshore Structures," International Symposium, April 6-7, 1978, Glasgow, Scotland.

130. Faulkner, D., "Remarks by Symposium Director," Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

131. Marsh, K. J., "Structural Fatigue Testing and the Fatigue Assessment of Offshore Structures," Integrity of Offshore Structures, International Symposium, April 6-7, 1978, Glasgow, Scotland.

132. Kasen, M. B., "DOT Program on Significance of Flaws in Girth Welds," NBS, Subcommittee on Line Pipe Steel Weldability Committee. WRC Progress Reports, Vol. XXXIV, No. 1, January 1979.

133. WRC Progress Reports, Vol. XXXIV, No. 1, January 1979.

134. Lewis, W. H., "The Impact of MIL-STD-1530 and MIL-1-83444 on Flaw Detection in Fatigue and Fracture Critical Parts for Air Frames," paper presented at Detection of Material and Fabrication Defects in the Transportation Industry, ASNT, June 11-13, 1979, Norfolk, Virginia.

135. Vanderveldt, H. H., et al, "Application of Fracture Control Technology in Navy Ships and Submarines," paper presented at 10th Symposium on Naval Structural Mechanics, Washington, D.C., Fracture Mechanics, The University Press of Virginia, 1978.

136. "Advanced Ship Structural Integrity Technology Planning Program," Summary, Contract No. N00024-76-C-4173, September 1976, The Boeing Company, Boeing Marine Systems, Seattle, Washington. Prepared for U. S. Naval Sea Systems Command, Washington, D. C.

137. Engstrom, W. D., "Advanced Ship Structural Integrity Technology Planning Program," Task 1, Final Report, Contract No. N000-24-76-C-4173, September 1976, The Boeing Company, Boeing Marine Systems, Seattle, Washington. Prepared for U. S. Naval Sea Systems Command, Washington, D. C.

138. Chene, J. J., "Weld Defects and Danger of Failure, " Proceedings, 8th World Conference on Nondestructive Testing, Cannes, September 6-11, 1976.

139. Salter, G. R., et al, "An Analysis of Defects in Pressure Vessel Main Seams," Welding and Metal Fabrication, Vol. 41, No. 4, April 1973.

140. Rogerson, J. H., "The Development of Efficient and Rational Sampling Schemes for the Non-Destructive Testing of Welded Fabrications." Welding Research International, Vol. 7, No. 5, 1977.

141. Volchenko, V. N., "Probability Basis for the Permissibility of Low Importance Defects in Welds, and the Advisability of Rectifying Them," Automatic Welding, Vol. 27, No. 10, October 1974.

142. Konkoly, T., "Evaluation of Radiographically Established Weld Defects by Numerical Consideration of the Tendency of the Weld Metal to Brittle Fracture," Welding Research Abroad, Vol. 19, No. 5, 64-73.

APPENDICES

APPENDIX I

QUALITY CONTROL SYSTEMS LOOP

Before entering into a re-examination of the key elements of QCSL as *a* method for quality and fatigue and fracture control it might be useful to put some important aspects of shipbuilding in perspective. As was said in Section IV, the quality of ships built today is much better than that of the Liberty ship era. However, there is room for further improvements. The basic material for commercial ship hull construction is the C-Mn steel of various grades and qualities. The bulk of the steel used is hot rolled. The chemistry and the mechanical and impact properties of these steels are checked by the producing steel mill; but the hot rolling finish temperature is not controlled. The ABS grade hull structural steels may be referred to as "uncharacterized" in that the fracture toughness values - determined still by the standard Charpy V Notch test method - display a broad scatter. As for CVN, it applies to neither static nor slow strain rate conditions.

Today's shipbuilding steels "ought to be re-analyzed statistically in a cooperative study among steel mills, shipbuilders and possibly code making bodies so as to determine the *ways* and means of minimizing the scatter in fracture toughness.

In a typical U. S. shipyard today there is no systematic plan set up which would allow a better understanding of the interrelationships among the essential elements of a comprehensive quality control scheme. The present system is open ended, isolated and reactive to crisis situations that may arise. A few examples, listed below, illustrate the points commonly cited in meetings called to discuss remedial steps for failure problems at hand:

1. “Establish a satisfactory level of notch toughness in the steels and weldments” has long been advocated. It is doubtful that any one of us knows with certainty what that “satisfactory level of fracture toughness" ought to be in light of the probabilities of the copious things that could go wrong in the total system.
2. “Develop properly designed crack arresters” has been viewed as a remedy to cracking in ships. Crack arrester steels have been known to fail, too.
3. Use in-process defect monitoring instruments so highly refined as to be able to “see”, "hear”, and “detect” with 100% reliability even micro-size flaws.
4. Eliminate fit-up problems.
5. Pay close attention to improper fabrication.
6. Employ more inspectors or perform 100% inspection on the product.

The point one has to recognize is that there is no single fix to all problems. A more reasonable approach would seem to be a comprehensive Quality Control Systems Loop. A good QCSL presupposes:

Understanding one’s own system.

Devising a comprehensive plan suitable to current needs within affordable limits.

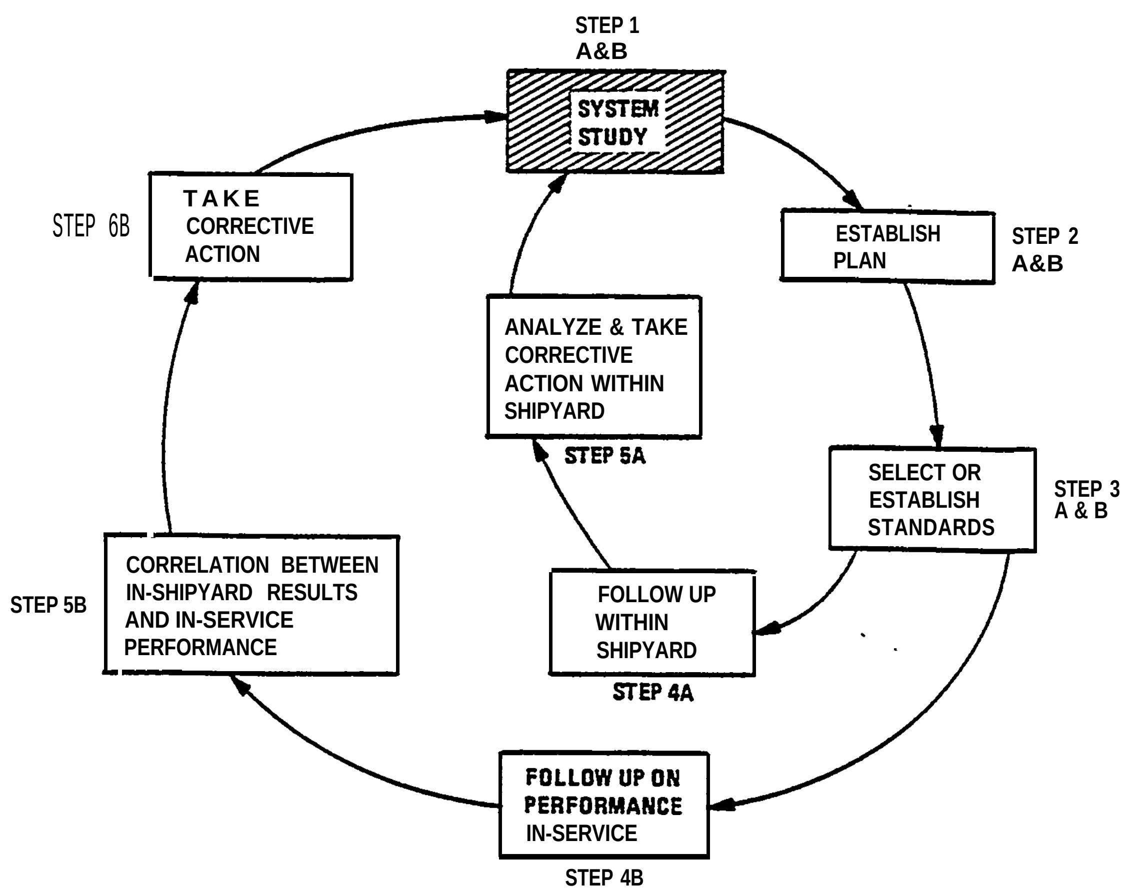
Selecting or establishing sensible standards.

Monitoring performance of the plan and the standards.

Correlating inspected and known results with in-shipyard and in-service performance.

Taking corrective actions as necessary to close the loop.

A schematic flow chart of QCSL might be as follows:



QCSL can be divided into Loop A and B - the former for the shipyard, the latter for the shipyard and the in-service performance results of the ship. Loop A yields short-range benefits, while Loop B gives long-range gains. QCSL is suitable for resolving single as well as multiple problems in an effective way.

APPENDIX II

TABLE 1

CHEMISTRY OF ALASKAN PIPELINE STEEL:

API 5LX 65

(Values given in weight percent)

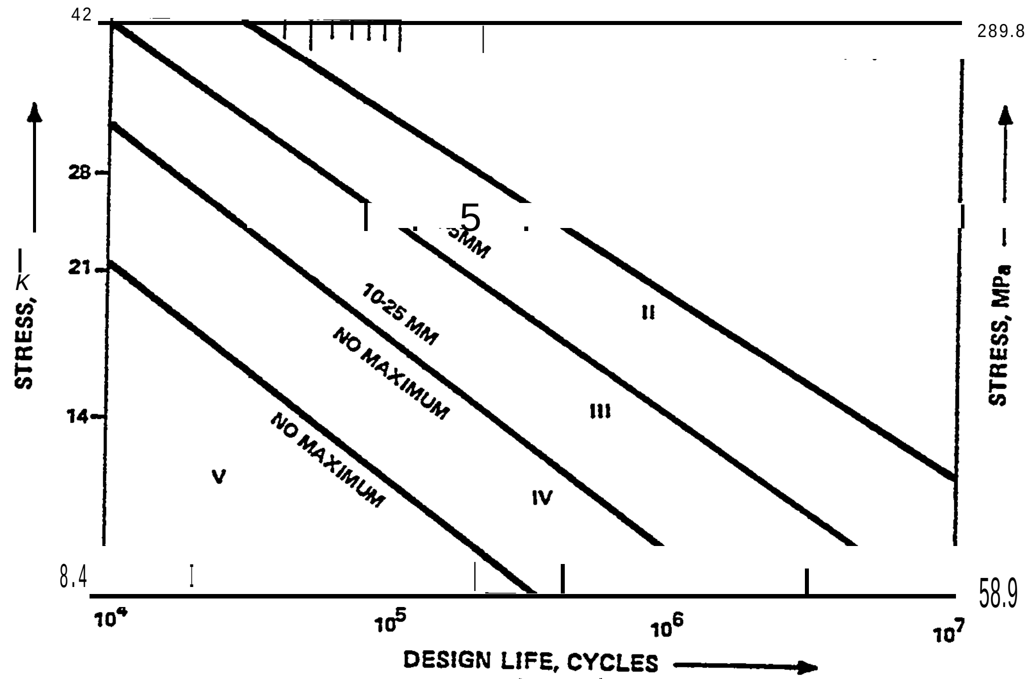
C	S	P	SI	Mn	V	Cu	Cb	Al	B
.10	.006	.017	.25	1.34	.06	.02	<.005	.023	<.001

Ni, Cr, Mo, Ti, Pb, Sn, Co all <.01

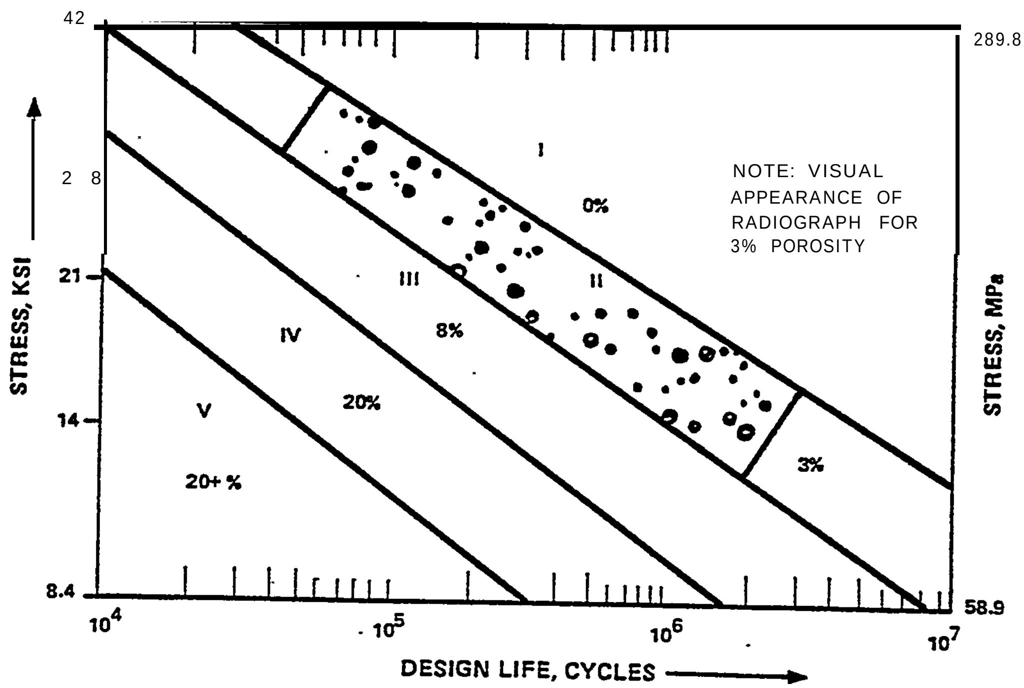
EXEMPLARY FORMAT OF PROPOSED STANDARDS

for As-Welded C-Mn Steel Weldments
and 5 Quality Categories.

(a) **SLAG INCLUSIONS:** (any thickness)



(b) **POROSITY:**



APPENDIX IV

WELD DISCONTINUITY VS. ENDURANCE

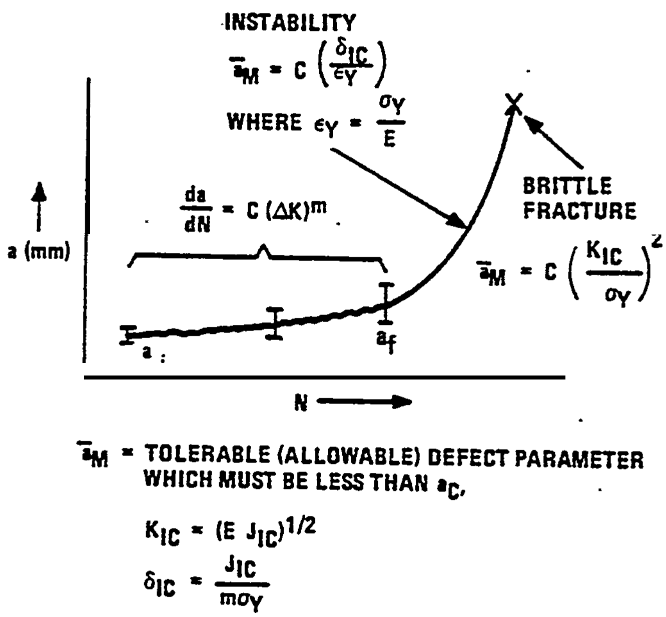


Fig. 1 Graphical illustration of fatigue failure mode from an incipient discontinuity.

Transportation
Research Institute